EXPERIMENTAL PHYSICS

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EXPERIMENTAL PHYSICS

A Laboratory Manual

BY

ALBERT EDWARD CASWELL, PH.D.

PROFESSOR OF PHYSICS,

UNIVERSITY OF OREGON

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PREFACE

Like most laboratory manuals of physics the present volume is the result of a process of evolution. It has evolved simultaneously with the author's text-book, "*An Outline of Physics*," which it is intended to accompany. However, it may be used in any course in general physics. Very little in the way of special apparatus is called for. In most of the experiments standard pieces of apparatus found in practically all laboratories are used. The instructions for each experiment contain a brief outline of the underlying principle and a reference to the corresponding pages of the author's text. Under "Work to be Done" the student is given general instructions for the performance of the experiment, but the details are omitted, so that the student must think his way through the experimental processes.

The list of experiments and the organization of the material are such that a well-balanced laboratory course requiring either one or two three-hour laboratory periods throughout the year may easily be selected.

Many of the experiments are divided into parts arranged in order of increasing difficulty. The better students may be expected to complete the experiment in the allotted time, while the poorer ones will omit one or more parts on account of lack of time or ability. Laboratories operating on a two-hour period basis may use only the first part of an experiment, or may devote two periods to one experiment. A number of experiments, especially those introducing a new topic, contain preliminary exercises, which serve to arouse the student's interest and cause him to realize the significance of the experiment he is about to perform. These exercises may be omitted at the discretion of the instructor. Refinements of importance to those engaged in advanced work or research but which distract the beginner and often cause him to lose sight of fundamental principles are omitted.

General instructions dealing with laboratory apparatus and methods, computations, etc., are included, also logarithmic and trigonometric tables and a list of references to more extensive manuals.

A. E. CASWELL

EUGENE, ORE.
September, 1928

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EXPERIMENTAL PHYSICS

GENERAL DIRECTIONS

Assignment of Laboratory Work. For convenience in administering the laboratory, especially where large numbers of students are involved, some system is usually adopted for assigning experiments. Whatever the system, the student should at the outset familiarize himself with it so that he may know something about the experiment he is to perform before entering the laboratory.

The method of making laboratory assignments followed with success by the author for a number of years is to assign each student a laboratory period, or periods, as the case may be, and also a group letter. A chart divided into rectangles is prepared with a vertical column of rectangles for each laboratory period and a horizontal row of rectangles for each laboratory group letter. Each student's name is written or printed in that rectangle belonging both to his laboratory period and his group letter. A second similar chart is prepared in which the vertical columns correspond to the weeks of the term, or semester, and the horizontal rows to the group letters, as before. The number of the experiment to be performed by any group during any week is written in that rectangle belonging both to the group and to the week. This second chart may be used year after year.

Objects of Laboratory Work. The student will bear in mind that the objects of laboratory work are two-fold, viz., (1) to acquire a first-hand acquaintance with physical facts and principles, and (2) to become trained in scientific methods and modes of thought.

Previous Preparation. Prior to the laboratory period the student should study carefully the instructions given in this manual concerning the experiment and the related lecture and text-book material. Outside reading on the experiment is also helpful. See the list of books given at the end of this volume.

He should also prepare an analysis of the experiment covering at least the following points:

(*a*) Definitions fundamental to an understanding of the experiment.

(*b*) Physical laws or principles either applied or tested in the experiment.
(*c*) Equations used in the numerical calculations. The meaning of the symbols used should be thoroughly understood.
(*d*) A brief description, illustrated by diagrams whenever conducive to clearness, and an outline of the experimental operations.

In the Laboratory. Upon entering the laboratory the student may find the table where he is to work indicated by the group letter (or whatever system is in vogue in the laboratory). Some of the apparatus may be found at the table, but any necessary apparatus which is not at the table may be obtained from the storeroom upon application to the storekeeper. This includes valuable pieces or those easily broken or lost.

Having obtained the apparatus to be used, the student should proceed with the experimental operations, observing the following recommendations:

(*a*) Be sure you understand the operation of the apparatus before beginning observations. If in doubt consult the instructor. Note the special instructions for the electrical experiments.
(*b*) Draw any diagrams which seem to be desirable.
(*c*) Note any numbers or distinguishing marks upon pieces of apparatus. You may need them sometime later.
(*d*) Whenever desirable (and this is usually the case) prepare with care a convenient table in which to record observed data and computed results. Before leaving the apparatus be sure that all necessary data have been recorded. Make your observations with the proper accuracy. See "Note on Significant Figures".
(*e*) Never sacrifice accuracy to speed.
(*f*) Handle all apparatus with care.
(*g*) If in doubt regarding the reliability of results obtained, consult the instructor.
(*h*) Directions and apparatus do not always correspond in all cases. Use your common sense.
(*i*) Do not remove apparatus from or to other tables. Do not take apparatus or books from the laboratory. Tables and laboratory should always present a neat and orderly appearance. Always leave apparatus in good condition. If you had to assemble it, take it down again before leaving

the table. Return borrowed apparatus to the storeroom after you are through using it. Watch the bulletin boards for special information concerning the laboratory work.

(*j*) Students are advised to keep their notes in a loose-leaf binder using paper $8\frac{1}{2}$ x 11 inches. Notes should be written clearly and legibly in ink. Use only one side of the paper. Numerical computations may be carried out on scratch paper, but data should always be recorded directly in the notes. Data should be tabulated whenever more than one measurement of a quantity is made.

(*k*) When two students work together both students should make at least one complete series of observations, but a student should record his partner's data, with suitable distinguishing marks, such as initials. In his report he may use both his own and his partner's data.

Reports. If possible, the report on an experiment should be handed in at the close of the laboratory period during which it is performed. In no case should it be handed in later than the next succeeding laboratory period. For the form of the notes see the preceding section.

The report on an experiment should contain:

(*a*) The student's name, partner's name (if any), number and title of the experiment, and date upon which it was performed.

(*b*) The data, diagrams, etc., mentioned in the preceding section.

(*c*) A sample calculation of the result, omitting details of the numerical work. All data should be used in the calculations, but the results alone should appear in the final report, preferably in a table of data.

(*d*) Discussion of probable sources of error and percentage of possible error in result, also the commonly accepted value of the quantity being determined, and the percentage difference between this value and the observed one.

(*e*) Graphs whenever called for in directions and also whenever likely to add to the value of the report.

(*f*) Conclusions drawn from the experiment.

(*g*) When the report is not completed within the laboratory period the student should file an approved data sheet with the instructor before leaving the laboratory.

Acceptance of Reports. No credit is allowed for an experiment until it has been "ACCEPTED." Within about a week of the time

a report is handed in it will be returned to the student. If the work and report are found satisfactory, the report will be marked "ACCEPTED," and the student will be given credit for the experiment, the experiment being graded according to the character and amount of work done. If not marked "ACCEPTED," the corrections indicated should be made as soon as possible, and certainly within two weeks, and the report again handed in.

Remarks on the Use of Apparatus. Since the accuracy of an experimental result often depends upon one measurement more than upon any of the others, that one should be carried out with the highest degree of accuracy possible. This fact often determines the method employed in making a particular measurement. This matter is discussed very briefly in Experiment 6 on Thermal Expansion, and in the notes on the vernier and the micrometer. Serious errors may arise in the use of micrometers as well as other pieces of apparatus through neglect of precautions to avoid "lost motion." For example, in a worm gear, which is being used to move a microscope, if the screw has been turning in one direction and its motion is reversed, it may make a considerable fraction of a revolution before the article which it actuates will begin to move in the opposite direction. In all such cases the apparatus should always be set by a movement from one, and only one, direction.

Similarly, it is often desirable to measure the rotation of a mirror. In such a case a "telescope and scale" or a "lamp and scale" method is employed. Sometimes very short distances are measured in this way. The apparatus is then called an "optical lever." See Experiment 1A.

Apparatus should also be selected for its adaptability to the use to which it is to be put. For example, a small object weighing but a few grams or ounces should not be weighed on a trip scale that is accurate only to 0.1 gm. with light loads, and only to 0.5 gm. with heavy loads. It should be weighed upon an analytical balance, which may have an absolute accuracy between 0.01 gm. and 0.001 gm. On the other hand, analytical balances are not suitable for weighing objects beyond two hundred grams. The capacity of laboratory balances varies from a few hundred grams to about five kilograms. Corrections to the readings of an analytical balance may be made for the buoyant force of the air, but as a rule such corrections are not justified.

When to make corrections to the reading of an instrument, and when not to, is often a puzzling question for the amateur. When the percentage error introduced by using the uncorrected

readings instead of the corrected readings is less than the percentage error which is unavoidably present in the final result due to some other cause, there is no object in making the corrections. For example, in some experiments it is necessary to determine certain temperatures with the aid of a chemical thermometer, which may be read to 0.1° C., or possibly to 0.05° C. Another temperature to be found is that of boiling water, which depends upon the atmospheric pressure. With the aid of a vernier the height of the barometric column may be determined to within 0.1 mm. Corrections to this height may be made for altitude,

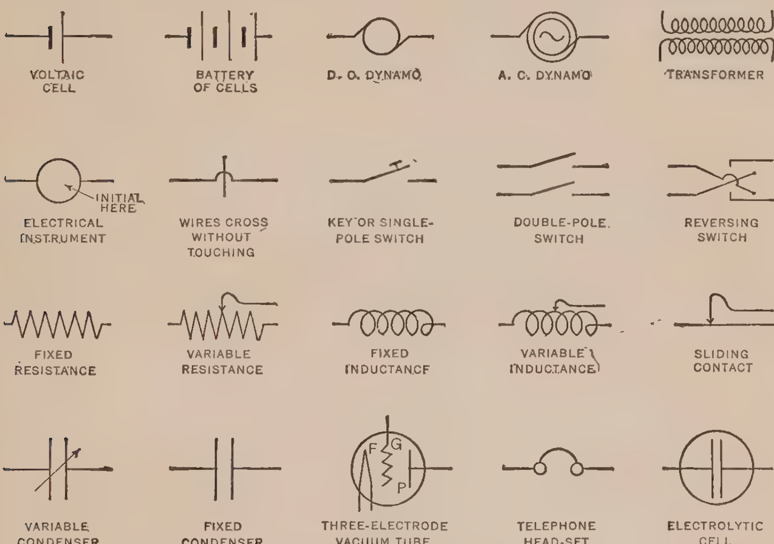


Fig. 1.—Conventional Electrical Symbols.

latitude and temperature. In general, these corrections are quite small. But it requires a difference in the barometric height of 1.35 mm. to make a difference of 0.05° C. in the boiling point. Hence, unless the corrections to the barometric height are approximately equal to, or greater than, 1.0 mm. they should be neglected. Obviously the converse is true, unless greater errors are inevitably present owing to other causes.

Special Instructions for Electrical Experiments. Always have a key or switch in series with all batteries or other sources of current, also with all electrical instruments, such as galvanometers ammeters, etc., unless a key is contained in the instrument.

Never close a circuit until certain that all instruments are properly connected. If you are using current from the lines installed in the laboratory, or have a standard cell in your circuit, ***get your set-up O. K.'d by an instructor before closing the switch.***

When first closing a switch always make a " tap contact," that is, close the circuit for as short a time as possible. While making the tap contact note the behavior of your instruments and other apparatus.

Remember that ***resistance boxes and galvanometers are not intended to carry large currents.*** Ammeters should always be protected by fuses of smaller capacity than the instrument. Voltmeters should never be connected in a circuit unless you are sure that the voltage is lower than the range of the instrument. In the case of double-range instruments, always connect to the higher range first.

Standard cells should never be used to supply current.

Failure to observe these instructions may result in damage to an instrument or other piece of apparatus. In such a case the student will be held strictly responsible.

In reports on electrical experiments the wiring diagrams should always be clearly shown unless the circuit is of the very simplest sort. Conventional symbols for various pieces of electrical apparatus should be used. A number of these are shown in Fig. 1.

1A. YOUNG'S MODULUS OF ELASTICITY BY STRETCHING

Read Caswell's *An Outline of Physics*, pp. 30–34.

The Principle of the Experiment. Whenever a wire is stretched by a force F, the elongation E produced is directly proportional to the stretching force (Hooke's law) and to the length L of the wire, but it is inversely proportional to the cross-sectional area A of the wire. It also depends upon the coefficient of elasticity of the material of the wire. This coefficient is commonly called Young's modulus of elasticity. The above facts are expressed by the relation $E = FL/YA$, where Y is Young's modulus. Hence,

$$Y = \frac{FL}{EA}. \qquad (1)$$

If the wire is stretched by the weight of a mass of m grams, the stretching force in dynes is given by $F = mg$ ($g = 980.7$) and if d is the diameter of the wire, $A = \pi d^2/4$, whence

$$Y = \frac{4mgL}{\pi d^2 E}, \qquad (2)$$

The wire to be tested is suspended from a steel chuck, which holds the upper end firmly, and near its lower end it passes through a small hole in a metal platform. A weight hanger is attached to a loop at the lower end of the wire. Weights are placed on the hanger to stretch the wire. It is best to load the hanger enough to completely straighten the wire before any measurements are made. Then add weights to produce the desired elongations. Moreover, these additional weights may cause the support that is holding the wire at its upper end to yield slightly and so vitiate the results. For this reason the weights to be added to the hanger should rest upon the support while the initial, or unstretched, length of the wire is being determined.

The elongation of the wire is such a small quantity that it must be measured with a high degree of precision in order to secure the percentage accuracy in this measurement that is easily obtained in the other measurements. To secure this accuracy, a device known as an optical lever is usually employed. This is a special case of the optical system known as "the telescope and scale."

A small plane mirror is mounted vertically on a horizontal platform which rests on three pointed legs. Two of these legs are directly beneath the mirror and the third is at a distance of a few centimeters behind it. The first-mentioned legs stand upon a rigid platform and the third rests upon a support which may move up or down. If it moves, the mirror is tilted forward or backward.

An observer looking through the telescope shown in Fig. 2, before the movement of the mirror, sees an image of the point A on the scale SS' attached to the telescope in coincidence with the cross-hairs of the telescope. When the third leg F attached to

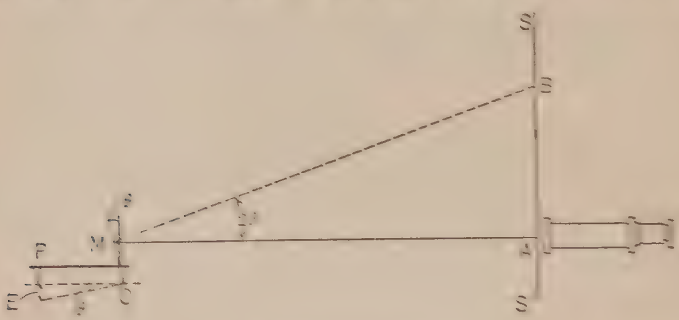


Fig. 2.—The Optical Lever.

the mirror M is depressed a distance E, causing the mirror support to rotate through an angle θ, the image of a different point B on the scale is observed to coincide with the cross-hairs in the telescope. The angle $AMB = 2\theta$. If the perpendicular distance from the line joining the points of the first two legs to the point of the third leg, i.e., FC, equals x, $E/x = \sin \theta$. But if the scale SS' is straight and perpendicular to the line MA, $AB/MA = \tan 2\theta$. If the angle θ is small, we have, as a close approximation,

$$2E/x = AB/MA, \qquad \text{or} \qquad E = \frac{x \cdot AB}{2 \cdot MA}. \qquad (3)$$

Sometimes an incandescent lamp with a straight vertical filament is placed at A instead of the telescope, and a convex lens is placed between it and the mirror M, so that an image of the filament is formed on the scale SS'. If the scale is translucent the position of the image can readily be seen. The equation is the same as before.

In this experiment the third leg of the optical lever rests on a small collar attached to the lower end of the wire and a few millimeters above the point where it enters the hole in the metal platform. Usually this leg may be adjusted, or the position of the collar may be adjusted, or the position of the telescope and scale may be adjusted, so that the image of the point A may be seen in the telescope before the stretching weights are removed from the upper support and placed on the hanger.

The length of the wire stretched is the distance from the lower side of the upper chuck to the upper side of the collar supporting the third leg of the mirror mounting. The distance this collar is depressed by the weights is the elongation E, and this may be calculated from equation (3).

Work to be Done. A. Place the wire to be tested in the apparatus. A wire having a diameter between 0.05 cm. and 0.10 cm. is a convenient size. Make the necessary adjustments of the wire and weights so as to straighten the wire, and adjust the optical lever, as indicated in the preceding discussion. One meter is a convenient distance at which to place the scale SS' from the mirror M. Determine the diameter of the wire at a number of places with a micrometer caliper, and measure its length to the nearest millimeter. Record the scale reading of the telescope, and then place a 1 kg. weight on the hanger and record the new reading. To be sure that the wire has not slipped in the chuck, or that some other accident has not occurred, it is advisable to return to the initial load, by removing the 1 kg. weight, and to observe whether the telescope reading is the same as at first. If it is not the same, try to discover the cause of the discrepancy. After you have found it, repeat the observation. Calculate the elongation produced.

Repeat, using 2 kg., 3 kg., 4 kg., and so on, until you use all the weights available or else reach the elastic limit of the wire. Be sure to return to the initial or "no load" readings between successive loadings.

When the elastic limit has been reached, the elongation begins to increase more rapidly than before, and the wire does not return to its original length. From equation (2) calculate Y, using the means of your measurements of the diameter, and the sums of all your loads and elongations.

B. Repeat part A, using a wire of the same material and same length, but of a different diameter.

C. Repeat part A, using a wire of a different material.

D. Using rectangular cross-section paper, plot graphs for

parts A, B, and C, using elongations as ordinates (i.e., plotted vertically) and the stretching forces in kilograms as abscissae (i.e., plotted horizontally). For each case draw the straight line which best represents your plotted points, disregarding any points whose positions may be due to excessive loading of the wire in question.

From the slopes of these lines determine the ratio of force to elongation (or vice versa) for each wire, and using these ratios recalculate the corresponding values of Y.

How do these results compare with the values obtained by using the sums of the forces and elongations? How do your results compare with those given in standard tables? Express differences in percentages of the standard values.

1B. YOUNG'S MODULUS OF ELASTICITY BY BENDING

Read Caswell's *An Outline of Physics*, pp. 30–34. See also Ferry and Jones *Practical Physics*, pp. 128–134 for derivation of formula.

The Principle of the Experiment. When an elastic solid is subjected to a stretching force it suffers an elongation which is proportional to the stretching force. If it is subjected to a force of compression, its length is shortened, the decrease in length being proportional to the force of compression. When a rectangular beam, or bar, which is rigidly fastened at the two ends, is subjected to a force perpendicular to its length applied at its mid-point, the relation between the distance L between the points of support, breadth B of the beam, its depth D and the deflection d of the mid-point which is produced by a force F, is expressed by the equation

$$Y = \frac{FL^3}{4dBD^3}, \tag{1}$$

where Y is Young's modulus, or coefficient, of elasticity for the material of which the beam is composed.

In this experiment the ends of the rod are supported upon knife-edges rigidly clamped to the edge of the table. Midway between the knife-edges a metal stirrup is suspended from the rod. By means of a micrometer screw electrical contact is made through a battery and a bell or sounder, whenever the stirrup is in contact with the micrometer screw. The micrometer screw is adjusted until it just touches the metal stirrup when no load is attached to the stirrup. By means of the stirrup a load is then attached to the rod, bending it downward. The micrometer screw is again adjusted until it just makes contact with the stirrup, and its second reading is observed. The difference between these two readings is the deflection of the rod.

Work to be Done. A. Several rectangular rods about a meter long and with cross-sections from 0.5 cm. to 1.0 cm. on a side are provided. Place one of these rods on the two knife-edges, having the knife-edges one or two centimeters from each end. Put the metal stirrup in place and adjust the micrometer screw as indicated in the preceding paragraph. Attach a load of, say, 100

grams to the stirrup and observe the deflection produced. Repeat this operation, using a number of different loads, choosing the loads so that the maximum deflection shall not exceed 1.0 cm. Tabulate the values of these loads and the deflections produced, also the ratios of the loads to the deflections. Disregarding any observation in which the value of this ratio differs notably from the others, add the loads together and also the deflections. Using the sum of these loads as the value of F in equation (1) and the sum of the deflections as the value of d in this equation, calculate the value of Young's modulus. F should be expressed in dynes. The distance between the knife-edges should be measured to the nearest millimeter, and the breadth and depth of the rod should be measured to the nearest 0.1 mm. with a vernier caliper.

If the cross-section of the rod is not square, Young's modulus should be determined with the rod on edge and also with its broad side on the knife-edges, and the results compared.

B. Determine Young's modulus for another material. Of the materials examined in parts A and B one should be wood and one metal.

C. Using a rod having a circular cross-section of radius R, determine Young's modulus after the manner of part A, substituting $3\pi R^4$ for BD^3 in equation (1).

D. Using a rod having a rectangular cross-section determine the deflections produced by the same load but with the knife-edges at several different distances apart, e.g., 100, 90, 80, and 70 cm. apart. On log-log cross-section paper plot deflections as ordinates and distances between knife-edges as abscissæ. Draw the straight line which best represents your results and determine the tangent of the angle which this line makes with the axis of abscissæ.

If the deflections are proportional to the cubes of the distances between the knife-edges, the tangent of this angle should be equal to 3. How close does your value agree with this?

2. MODULUS OF RIGIDITY BY THE TORSION LATHE

Read Caswell's *An Outline of Physics*, pp. 30–35.

The Principle of the Experiment. Whenever a rod is twisted there is a tendency for one layer of the material of the rod to slide over the next one to it. This results in a deformation of each section of the rod. According to Hooke's law of elasticity, if the rod is perfectly elastic, the twist produced in the rod is directly proportional to the force applied. An exact mathematical analysis of the problem leads to the conclusion that the angle through which the rod is twisted is directly proportional to the length of the rod and to the fourth power of its diameter, and also to the elasticity of shape, which is a constant of the material, known as the coefficient of rigidity, or as the modulus of rigidity. Moreover, the effect of the force upon the rod is not simply measured by the force itself, but by the product of the force and the perpendicular distance of its line of action from the axis of the rod. This product is called the moment of the force.

One end of the rod to be tested is rigidly clamped in a chuck mounted in a clamp attached to the laboratory table top. The other end is clamped in a chuck attached to the center of a wheel which is free to rotate in another clamp, which is attached to the table top, the axis of rotation being the longitudinal axis of the rod. A divided circle is engraved on the wheel. A strap is wrapped around the circumference of the wheel and a weight is attached to the end of the strap. If the wheel rotates through θ degrees when a mass weighing m grams is attached to the strap, θ is related to the length L, the diameter d, and the modulus of rigidity μ, by the equation

$$\theta = \frac{5760\,mgrL}{\pi^2 d^4 \mu}, \tag{1}$$

where r = radius of the wheel, and $g = 980.7$. The modulus in this case is expressed in dynes per square centimeter. Solving equation (1) for μ, we obtain

$$\mu = \frac{5760\,mgrL}{\pi^2 d^4 \theta}, \tag{2}$$

Work to be Done. A. Clamp the rod to be tested in the chucks and attach a sufficient weight to the end of the strap to take up any slack or lost motion in the apparatus. The weight hanger may be sufficient to do this. Note the angle marked on the circumference of the wheel which coincides with the index mark. Add a 1 kg. weight to the strap and again read the angle. θ can be obtained from these two readings, but will not be the difference between them if the angle marked 0° has moved past the index. Remove the 1 kg. weight and see whether the wheel comes back to its original position. If it does not, the chances are that the rod has slipped in one of the chucks and the chucks should be readjusted and the operation repeated.

Measure the length of the rods between the chucks to the nearest millimeter, and measure the diameter of the rod at a number of places with a micrometer caliper. Also measure the radius of the wheel as accurately as possible, measuring to the center of the strap.

Sometimes the circumference of the wheel is not graduated, but two pointers are attached to the rod near its ends and these pointers move over graduated scales. θ then is the difference between the two angles swept out by the pointers, and L is the distance between their centers.

Repeat the preceding measurements using three or four different weights. The values of these weights should be chosen with reference to the diameter, length and material of the rod. The weights applied should not be so great as to result in giving a permanent twist to the rod. If this occurs it will be revealed by the fact that the angle of twist increases more rapidly than the load and the rod does not return to its original position when the weight is removed.

Calculate μ from equation (2), using the sums of the values of m and θ, and the mean of the values of d.

B. Repeat part A, using a rod of the same material but smaller diameter.

C. Repeat part A, using a rod of a different material. If the first rod was of metal, this one may be of wood.

D. Using rectangular cross-section paper, plot graphs for parts A, B, and C, using angles of twist as ordinates (i.e., plotted vertically), and weights attached to the strap to produce the twists as abscissæ (i.e., plotted horizontally). For each case draw the straight line which best represents your plotted points, disregarding any points whose position may be due to excessive twisting of the rod in question.

From the slopes of these lines determine the ratio of the weight to the twist produced (or vice versa) for each rod, and using these ratios recalculate the corresponding values of μ. How do these values compare with those obtained in parts A, B, and C? How do they compare with those obtained in standard tables? Express differences in percentages of standard values.

3. ARCHIMEDES' PRINCIPLE AND SPECIFIC GRAVITY

Read Caswell's *An Outline of Physics*, pp. 14, 43 and 44.

The Principle of the Experiment. According to Archimedes' Principle, a body immersed in a fluid at rest loses in weight an amount equal to the weight of the displaced fluid. A floating body displaces a volume of fluid whose weight is equal to its own weight.

This principle enables us to determine the specific gravity of a substance, which is the ratio of the mass of a given volume of the substance to the mass of an equal volume of water. Objects upon the surface of the earth or near to it are usually immersed in air, and so their observed weights are less than their actual weights by the weight of the volume of air which they displace. When dealing with solids and liquids, the correction for the weight of the air is so small that we usually neglect it. This procedure would not be justified if we were dealing with a gas, e.g., a helium-filled balloon.

Neglecting the buoyancy of the air, if the weight of a body in air is W_1 and its weight when immersed in water is W_2, its specific gravity is given by

$$s = \frac{W_1}{W_1 - W_2}. \tag{1}$$

Work to be Done. A. A cylinder is provided which exactly fills a small bucket. Suspend the cylinder and bucket from one arm of the balance and either counterpoise or weigh them. Then with the cylinder hooked underneath the bucket bring a vessel of water up underneath the cylinder until it is completely under the surface of the water. The water should not touch the bucket, however. How does this affect the equilibrium? Then carefully fill the bucket just even full of water. How does this affect the equilibrium? If the cylinder with the bucket is not available, weigh a cylinder in air and then submerge in water. Measure its dimensions and compute its volume, and compare its loss in weight with its volume and the weight of an equal volume of water. What are your conclusions in either case?

B. An irregular heavy solid is provided. Weigh it first in air, and then immersed in water, and from these weighings com-

pute the specific gravity of the solid. Tabulate the data and all the work. What are the advantages of this method?

C. Weigh in air a block of wood or other object light enough to float, then attach to it a "sinker" hung by a wire or thread so that the sinker is in water but the light object in air; make a third weighing with both in water. From these three weighings find the loss of weight of the light object in water and its specific gravity.

D. A piece of wood is loaded at one end so as to make it float vertically in water. From its dimensions and the depth to which it sinks, compute the weight of water it displaces, and compare this with the weight of the stick. Show how this stick could be used to find the specific gravity of other liquids. With the hydrometers furnished determine the specific gravities of a liquid lighter than water and one heavier than water.

E. Place a vessel of water on one pan of a balance. Weigh or counterpoise the heavy solid whose weight was determined in part B, then lower it into the water until it is entirely submerged, but not touching the dish, and weigh again. How does the apparent increase in weight of the water compare with the loss previously noted? How do you explain the result?

4. SURFACE TENSION BY DIRECT METHOD

Read Caswell's *An Outline of Physics*, pp. 45–49.

The Principle of the Experiment. When a horizontal wire is dipped beneath the surface of a liquid and then lifted vertically the wire draws up the surface film of the liquid in a double layer. If γ = the coefficient of surface tension, i.e., the force exerted by a centimeter length of edge of film, the downward force F exerted upon the wire $= 2L\gamma$, where L = length of the wire.

One method of determining surface tension consists in measuring the force directly which is exerted by a known width of film. A brass fork is immersed in the liquid and then raised until a film is formed between the prongs, and the force exerted by the film measured. In this case L is the distance between the prongs. The force is measured by attaching the fork to the spring of a Jolly spiral spring balance and observing the elongation of the spring produced by the force of surface tension. Then a known weight is attached to the spring and the elongation produced by the known force is determined.

If a is the distance in centimeters the force of surface tension stretches the spring and b is the distance a force of one gram stretches it, then $F = a/b$, where F is expressed in grams weight and

$$\gamma = ga/2Lb, \tag{1}$$

where γ is expressed in dynes per centimeter.

Work to be done. A. Nearly fill a beaker with distilled water and place it upon the platform of a spiral spring balance. Adjust the distance between the platform and the reference line on the upright standard so that when the index on the lower end of the spring is in the same horizontal plane with the reference line the lower side of the cross-bar of the fork is about 3 mm. above the surface of the liquid. This distance should be nearly as great as possible without causing the breaking of the film. Lift the beaker until the cross-bar of the fork is immersed, then lower it again to the platform. Adjust the upper support of the spring until the index is again even with the reference line. (If the line is etched on a mirror, the index, line, and the image of the index should lie in a straight line.) Record the position of the support. Break the film. Again adjust the support and record its new

position. The distance between these two positions represents the elongation of the spring produced by the force of surface tension. Place a small weight (say 2 gm.) in the scale pan and determine the elongation produced thereby. Calculate the force of surface tension. Measure the width of the fork and calculate γ. Make at least two concordant determinations of γ.

B. Repeat part A, using a soap solution. Can you reconcile the fact that the soap film may be stretched much farther than the water film before breaking with the relative values of γ?

C. Repeat part A, using alcohol or other liquid.

5. VISCOSITY OF LIQUIDS

Read Caswell's *An Outline of Physics*, pp. 57–58.

The Principle of the Experiment. The student is familiar with the fact that a liquid like water runs out of a vessel more freely than one like molasses or honey. In all liquids which are in motion there is a tendency for one layer of the liquid to drag the next one to it, or to hold it back, depending upon the relative motion of the two layers. This phenomenon is known as viscosity.

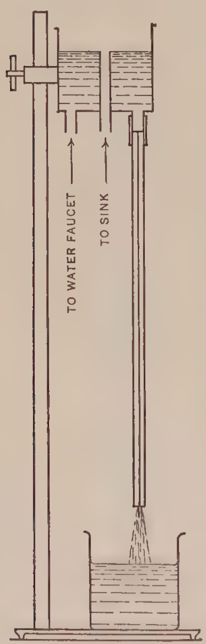


FIG. 3.

The coefficient of viscosity, or briefly, the viscosity of a substance may be measured by means of the apparatus shown in Fig. 3. A piece of capillary glass tubing L cm. long is attached by means of a rubber connection to one of the orifices in the bottom of a constant level overflow cup. The other orifice is connected to the water faucet, and the flow of water is regulated so that there is a constant trickle from the overflow pipe.

If V is the volume of a liquid of density D which flows through the capillary tube in the time t, the viscosity,

$$\eta = \frac{\pi h r^4 D t g}{8LV}, \tag{1}$$

where h = the vertical distance between the liquid surface in the overflow cup and the bottom end of the capillary tube, r = the radius of the capillary, and g = 980.7, when the centimeter-gram-second system of units is used. η is then expressed in dynes/cm^2.

Work to be Done. A. Clean the capillary tube by forcing through it a number of times in succession chromic acid, distilled water, and alcohol, and finally dry it by sucking dry air through it. Determine its diameter by running a small amount of mercury into it. Measure the length of the mercury thread in the tube, then run the mercury out into a watch glass and carefully weigh it. From the density of the mercury and the length of the

mercury thread, determine the diameter of the capillary bore. Measure L and h.

Determine the viscosity of water at the temperature it has when coming from the cold water faucet by catching the volume V, which flows through the capillary tube in the time t, in a beaker. Note the temperature of the water. Repeat, using water from the hot water faucet.

B. Repeat part A, using alcohol at room temperature. It may be more convenient to use a funnel instead of the constant level overflow cup, and to pour the liquid into the funnel slowly so as to maintain the surface level in the funnel as nearly constant as possible.

C. Repeat part B, using a light machine oil.

6. THERMAL EXPANSION OF SOLIDS AND LIQUIDS

Read Caswell's *An Outline of Physics*, pp. 36–38 and 58–60.

Preliminary Exercise. A brass ball is of such a size that its diameter is almost exactly the same as that of the opening in a brass ring. If the ball will not slip through the ring, try the effect of heating the ring. If the ball slips through the ring, see what happens when the ball is heated. Thin strips of two different metals are welded together so as to form a bar. Heat the bar and observe the results. A glass bulb with a capillary neck is filled to the top of the neck with water at about the same temperature as the room. Place the bulb in a mixture of crushed ice and water and observe the behavior of the water in the capillary tube.

The Principle of the Experiment. Many properties of materials change with change in temperature, and for many purposes it is important to know the amount of this change. For purposes of comparison a unit in which the property in question is measured is taken under certain "standard" and easily reproducible conditions, and the change produced in this unit by a unit change in temperature is determined. This change in the unit of the property is called the temperature coefficient of the property. Thus, if the length of a body increases when its temperature is raised, it possesses the property of linear expansion and the unit in which the expansion is measured is centimeters, feet, or inches. Hence, if a is the coefficient of linear expansion, L_1 the length before heating and L_2 the length after heating, and if t_1 and t_2 are the corresponding temperatures,

$$a = (L_2 - L_1)/L_1(t_2 - t_1). \tag{1}$$

The student should be able to show that any temperature coefficient depends only upon the unit of temperature employed and the initial temperature. Whenever the temperature coefficient is relatively large (e.g., greater than 0.00002 per °C. or 0.00001 per °F.) it is customary to take $t_1 = 0$. Why?

Work to be Done. A. A metal rod is surrounded by a jacket through which water or steam may be passed. When the temperature of the rod is altered, its length changes, and since this change is very small in comparison with the length of the rod, the

change in length must be measured with a much higher degree of precision than the length itself. It is easier to measure the length to 1.0 mm. than it is to measure the change in length to 0.001 mm. and yet a mistake of 0.001 mm. in the measurement of the change in length will result in approximately the same percentage error in the result as a mistake of 1.0 mm. in the measurement of the total length.

The change in length may be measured by a traveling vernier, or micrometer, microscope which is focussed upon a scratch on the rod. The microscope is moved parallel to the length of the rod by a worm gear. Or the change in length may be measured by the movement of a lever which multiplies the expansion of the rod by the ratio of the lever arms.

Since the coefficient is small, its value near room temperature will not be perceptibly different from its value at 0° C. Pass tap water through the jacket until the scale reading becomes stationary. Measure the length of the rod as closely as possible with a meter stick. Determine the temperature of the water. Focus the microscope on the scratch or note the vernier or lever scale reading. Then pass steam through the jacket and determine the change in length of the rod. From the barometric pressure and tables find the temperature of the steam. Calculate the linear expansion coefficient and compare your result with that given in the tables for rods of the same material, and state your percentage error.

B. A glass bulb having a volume of about 10 cc. and a long capillary tube attached upon which the total volumes of bulb and tube are etched for a certain temperature is filled with kerosene. Place the bulb in a bath of melting ice and read the volume of the liquid after it ceases to change. Repeat in a water bath at a temperature close to 50° C. Calculate the apparent cubical expansion coefficient using the formula given above with V taking the place of L. Add the cubical expansion coefficient of glass to this result. Why? Compare your results with the value given in the tables, and state your percentage error.

7. ELASTICITY OF AIR—BOYLE'S LAW

Read Caswell's *An Outline of Physics*, pp. 61–63.

Preliminary Exercise. Practically every one is familiar with the fact that as more air is pumped into an automobile tire, the greater the pressure of the air in the tire becomes. Let the air out of an automobile tire. The pressure inside the tire is then atmospheric pressure, but the tire gauge reads zero. Connect an automobile pump to the tire and then make, say, 20 full strokes of the pump and again read the pressure. Repeat this operation a number of times. At each stroke of the pump a certain volume of air at atmospheric pressure is forced into the tire, so that the mass of air pumped into the tire is proportional to the number of strokes of the pump. Note the way the force which must be exerted upon the piston of the pump varies through the length of the stroke and as the pressure in the tire is increased.

The Principle of the Experiment. According to Boyle's Law, as long as the temperature of a gas is kept constant, the pressure of the gas is proportional to its density, or if the volume of a given mass of the gas is altered in any way, the pressure of the gas is inversely proportional to its volume. Boyle's law is expressed by the following equation:

$$pv = \text{a constant.} \tag{1}$$

The apparatus used consists essentially of a closed tube in which some air is entrapped and an open tube which serves as a manometer, both of which are connected to a mercury reservoir. Either by raising the reservoir or by forcing the mercury out of it, the mercury column can be raised in both the open and closed tubes. The pressure in the closed tube (in cm. of mercury) is equal to the atmospheric pressure (also in cm. of mercury) plus the distance in cm. the level of the surface of the mercury in the closed tube is below that in the open tube. If the closed tube is of uniform cross-section, the volume of entrapped air is proportional to the length of the air space and may be considered equal to it.

Work to be Done. A. With the mercury surface in the open tube as low as possible, observe the heights of both mercury surfaces. Make a series of observations raising the level of the mercury in the open tube about 20 cm. each time until it is about

as high as possible. Raise the mercury level slowly and wait until the mercury surface is stationary before taking readings. Why? Make a similar set of readings as the mercury surface is lowered. Tabulate data thus:

	Readings					
	1st	*2nd*	*3rd*	*4th*	*5th*	*etc.*
Constant temp. in deg. C.	....	....	....	....	....	....
Atmo. press. P in cm. mercury	....	....	....	....	....	....
Height h of top of closed tube	....	....	....	....	....	....
" h_c of mercury in closed tube	....	....	....	....	....	....
" h_o of mercury in open tube	....	....	....	....	....	....
Head of mercury $p' = h_o - h_c$	....	....	....	....	....	....
Total press. $p = P + p'$	....	....	....	....	....	....
Vol. prop. to $h - h_c = v$	....	....	....	....	....	....
Product of press. $\times$ vol. $= pv$	....	....	....	....	....	....

B. With pressures as ordinates and volumes as abscissæ, plot your results on rectangular cross-section paper. Again, using pressures as ordinates and the reciprocals of the volumes as abscissae, plot your results on rectangular cross-section paper. If equation (1) is true, the straight line which best represents your results will pass through the origin.

C. Using pressures as ordinates and volumes as abscissæ, plot your results on log-log cross-section paper. Draw the straight line which best represents your results. If equation (1) is true, $p = c/v$, or $p = cv^{-1}$. The intercept of this line on the p-axis should equal c, and the tangent of the angle which it makes with the positive direction of the v-axis should be equal to (-1). How does c found in this way compare with the average values of the product pv in your table? Is the tangent equal to (-1)?

8. THERMAL EXPANSION OF A GAS—CHARLES' LAW

Read Caswell's *An Outline of Physics*, pp. 63–65.

The Principle of the Experiment. Whenever the temperature of a gas is raised, if the pressure exerted upon it is kept constant, the volume of the gas increases, the coefficient of cubical, or volume, expansion of the gas being given by the equation

$$\alpha = \frac{v_t - v_0}{v_0 t}. \tag{1}$$

where v_0 = volume at 0° C. and v_t = volume at t° C.

In general, the volume of the containing vessel will also change with the temperature, and if the volume of the container increases, the apparent increase in volume of the gas will be less than the actual increase. The student should be able to prove that the difference between the apparent increase in volume and the actual increase is equal to the increase in volume of the material of the container having a volume equal to the initial volume of the gas, and that the true expansion coefficient may be found by adding the cubical expansion coefficient of the material of the container to the apparent cubical expansion coefficient of the gas.

The absolute, or Kelvin, scale of temperature is defined in such a way that the numerical value of the temperature is proportional to the volume of a given mass of gas, assuming that the thermal coefficient of volume expansion, referred to 0° C., has the same value for all ranges of temperatures as it has at ordinary temperatures.

Work to be Done. A. Weigh on an analytical balance an empty specific gravity bottle having a capacity of about 100 cc., and provided with a tightly-fitting glass stopper through which there is a small capillary opening. If such a bottle is not available, a small flask with a piece of rubber tubing attached to the neck and closed with a pinch-cock will serve the purpose.

Immerse the bottle in a vessel of water with the stopper downward so that no air may escape and thus permit water to run into the bottle. Warm the water until it boils gently, noting that as the water becomes warmer, bubbles of air escape from the bottle. When no more air escapes from the bottle, begin lowering the temperature of the water by adding cold water. In this way,

reduce the temperature of the water to that of melting ice. That is, the vessel should finally contain a mixture of cracked ice and water. After leaving the bottle in this mixture until there is a reasonable assurance that the air is at the temperature of the water, place your finger over the capillary opening and remove the bottle from the water.

Turn the bottle right side up, dry off the outside carefully, and weigh the bottle and contents again. From the barometer reading find the boiling point of water. From the three weighings calculate the volume of the air at 0° C. and its apparent volume at the boiling point of water. From these volumes and the temperature, t, of the boiling point calculate the apparent coefficient of volume expansion of air. Correct this coefficient for the expansion of the glass.

B. Using the true value of the coefficient of expansion, and the values of v_0 and t found in part A, calculate the true volume of the air at the temperature t with the aid of equation (1). On rectangular cross-section paper, using volumes as ordinates and temperatures as abscissæ, plot the volumes at 0° C. and at the boiling point of water. Draw a straight line through these two points and prolong it until it intersects the temperature axis. The temperature at this point of intersection should be the zero of the absolute scale, since the corresponding volume is zero. According to your experiment, what temperature on the Centigrade scale corresponds to zero on the absolute scale? How closely does this agree with the accepted value?

9. PRESSURE COEFFICIENT OF A GAS—THE AIR THERMOMETER

Read Caswell's *An Outline of Physics*, pp. 63–69.

The Principle of the Experiment. Whenever a mass of gas is confined in a vessel in such a way that its volume is kept constant, if the temperature of the gas is increased, the pressure it exerts upon the walls of the containing vessel is also increased. The increase of pressure is proportional to the increase of temperature. The absolute, or Kelvin, scale of temperature is defined in such a way that the numerical value of the temperature is proportional to the gas pressure, assuming the law holds for all ranges of temperature and that the proportionality factor is that which is found at ordinary temperatures.

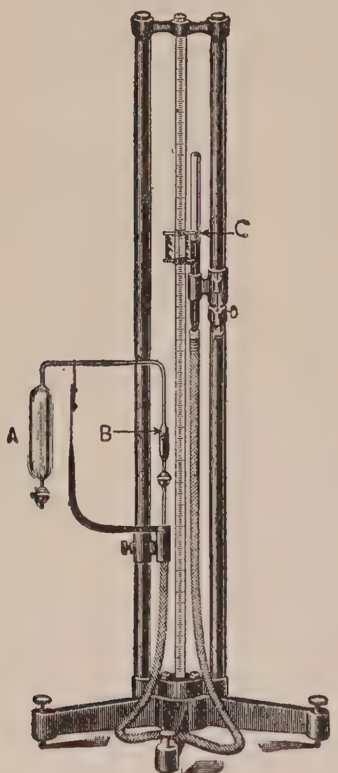


FIG. 4.—The Air Thermometer. (Courtesy of the Central Scientific Company.)

A glass bulb A, Fig. 4, is connected by some capillary tubing to a large glass tube. At the point of juncture B, a small index is sealed into the glass tube or an external index is set at this point. The large glass tube is connected by rubber compression tubing to the glass tube C. The tube between B and C is filled with mercury, and a small amount of sulphuric acid is placed in A to keep the contained air dry. The tube C is always kept adjusted so that the mercury surface coincides with the index at B. Consequently the pressure exerted on the air in A is atmospheric pressure in cm. of mercury, plus the number of cm. the mercury level in C is above that in B. If P be the atmospheric pressure expressed in centimeters of mercury, p_0 the difference in level when the bulb A

is in the melting ice (N.B. p_0 is negative when the level in C is below that in B) and p_t the difference in level when the bulb A is in boiling water, then the coefficient of pressure, volume constant, is

$$b = (p_t - p_0)/(P + p_0)t. \tag{1}$$

Work to be Done. **A.** Place the bulb in a vessel filled with cracked ice and just enough water to fill the interstices. The whole of the bulb A should be below the surface of the water. After the pressure has ceased to change, determine p_0.

Replace the ice bath by a bath of water, then boil the water gently and determine p_t. Stir the water well and be sure that the air in the bulb has come to the temperature of the water. CAUTION! Before leaving the apparatus lower the tube C as far as possible. Read the barometer and from the tables determine the boiling point of water for that day. This will be the temperature t. Calculate b. Enumerate all the factors of which you have not taken account which may affect the value obtained, and state in what way each will affect it.

What effect has the expansion of the glass bulb A upon the coefficient of pressure as calculated from your observations? If you add the cubical expansion coefficient of glass to the observed pressure coefficient of the gas, will this correct for the change in the volume of the bulb? Why? The gas in the tube leading from the bulb A to the surface of the mercury was not heated to the boiling point. What effect will this have on your value of b?

B. Having corrected the value of b, determined from equation (1), for the change in the volume of the bulb and for the volume of unheated air between the bulb A and the mercury column, if this is large, substitute this value of b in equation (1), and using the same values of P, p_0 and t as before, calculate p_t. On rectangular cross-section paper, using pressures as ordinates and temperatures as abscissæ, plot the values of the gas pressure at 0° C. and at the boiling point of the water. Draw a straight line through these two points and prolong it until it intersects the temperature axis. The temperature at this point of intersection should be the zero of the absolute scale, since the corresponding pressure is zero. According to your experiment, what temperature on the Centigrade scale corresponds to zero on the absolute scale? How closely does this agree with the accepted value?

10. SPECTRUM ANALYSIS

Read Caswell's *An Outline of Physics*, pp. 77.

Preliminary Exercise. Hold a glass prism in sunlight and observe the brilliant spectrum formed by the light from the sun which has passed through the prism, ranging from red, through orange, yellow and green, to blue and violet. This series of colors is the same as that of the rainbow, and its origin is the same. Hold the prism with its axis parallel to a filament of an incandescent lamp and view the filament through it. It will be necessary to hold the prism so that the angle formed by the line from filament to prism and from prism to eye is obtuse, say, 120°. View a number of objects through the prism in this way and note the results.

The Principle of the Experiment. Whenever an atom or a molecule of a substance gives out light, the light has a characteristic color or combination of colors. This color or combination of colors can be determined by means of a spectroscope. The essential parts of a spectroscope are a narrow slit, through which the light enters the instrument, one or more glass prisms which separate it into its component colors and a telescope through which the resulting spectrum is viewed. The axis of the prism, or prisms, is parallel to the slit of the spectroscope, and when one looks into the telescope part of the spectroscope he sees a series of images of the slit in the form of bright lines, or colored bands. If lines appear at one end of the field of view of the telescope they are red, next to the red lines orange lines may occur, then yellow, green, blue-green, blue, and finally violet at the other end.

In the better spectroscopes a side tube is provided which contains a glass or celluloid scale, and when a lamp is placed at the end of this tube, or sunlight is reflected into it, the scale is seen in the field of view of the telescope either immediately above or below the lines of the spectrum. The positions of the lines which are characteristic of any particular substance may be located on this scale. Then whenever we find the same set of lines in the same positions we know that we have the same substance.

The width of the slit of the spectroscope is adjustable and if a wide slit is used, the lines seen in the telescope are broad and difficult to locate exactly. After the position of a line is known approximately the slit may be narrowed until further narrowing causes the line to disappear altogether.

Work to be Done. A. Hold the spectroscope so that the light from an open window illuminates the slit and view the spectrum of the light from the sky which is practically the same

as sunlight. See if you can narrow the slit of the spectroscope until you can see fine dark lines crossing the spectrum at a number of places. These lines are called the Fraunhofer lines, and are difficult to discern except with a fairly good spectroscope.

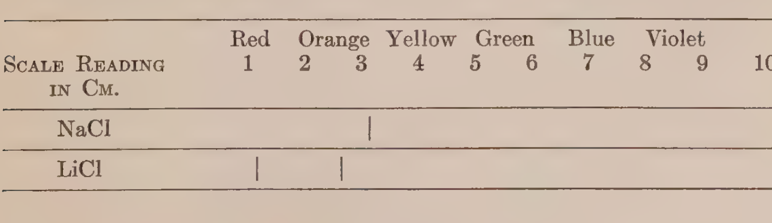
B. Repeat part A, placing a lamp of some sort in front of the slit of the spectroscope.

C. Adjust a Bunsen burner until it gives a flame which is almost, if not altogether colorless. Then spray a solution of common salt into the flame. If no apparatus is available for spraying the salt into the flame, a piece of asbestos may be soaked in the solution and held in the lower part of the flame. The flame should be strongly colored by the salt. With common salt (NaCl) the flame will be a yellowish-orange. Examine the flame with the spectroscope and record the position of the bright yellow line which you see. This line is characteristic of sodium and appears in nearly all spectra because a very small trace of sodium in the gas will color the flame. If the slit is narrow enough and the spectrum long enough, this line may appear as two lines very close together.

D. Repeat part C, using a number of salts, e.g., potassium chloride (KCl), lithium chloride (LiCl), strontium chloride ($SrCl_2$), and calcium chloride ($CaCl_2$).

E. If spectrum tubes are available, one of them may be connected to an induction coil and the tube mounted so that the long narrow capillary part of the tube is directly in front of the slit and parallel to it. When an electric discharge is passing through the tube the spectrum which is emitted by the gas in the tube may be observed in the spectroscope. The instructor should connect up the spectrum tube and the induction coil and make the necessary adjustments of the induction coil so that the tube will function most efficiently. The student should be very careful to keep away from the wires leading from the induction coil to the tube and the tube should not be allowed to touch the spectroscope.

F. On rectangular cross-section paper prepare a chart from your data similar to the one shown below, in which the positions of the lines corresponding to the different substances are shown.



11. DENSITY OF AIR AND HYGROMETRY

Read Caswell's *An Outline of Physics*, pp. 61–69, 102–111.

The Principle of the Experiment. The density of water vapor is 0.625 that of dry air. From Boyle's and Dalton's laws it may be shown that, if D and D_m are the densities of dry and moist air, respectively, P = atmospheric pressure, and p = saturated vapor pressure,

$$D_m = D(P - 0.375\,p)/P. \tag{1}$$

What effect should an increase in the amount of water vapor in the atmosphere have upon the barometer reading? Why? What conditions, other than the presence of water vapor, affect the reading of a barometer?

The pressure of the water vapor in the atmosphere may be found by experimentally determining the dew point and finding from tables the saturated vapor pressure of water for that temperature. The dew point may also be found with the aid of tables from the readings of the wet and dry bulb thermometers in air which is circulating freely.

The relative humidity is the ratio of the saturated vapor pressure at the dew point to the saturated vapor pressure at the temperature of the air. It is also equal to the ratio of the absolute humidity under the existing conditions to the absolute humidity if the air were saturated.

Work to be done. A. Weigh a burned out lamp globe on a sensitive balance. Break off the tip carefully by filing a circle around it and tapping gently. If it has no tip a small hole may be made by plying a small hot flame on the bulb at one point for a short time. A balloon flask may be used instead of the lamp globe. When this is done, the flask should be exhausted by a good air pump. The stopcocks on the flask must be air-tight. Force a jet of air which has passed through a drying tube into the lamp globe for several minutes. The air should be pumped rather slowly so that it may be thoroughly dried in passing through the drying tube. Dry air is denser than ordinary moist air. How should the bulb be held so that the dry air may displace the moist? Weigh again, including all pieces in the weight. Fill the bulb with water and weigh on a rough balance. From the first two weighings, calculate the mass of dry air which fills the bulb under existing conditions of temperature and pressure.

From the first and third weighings and the density of water, calculate the volume of the bulb. Calculate the density of the dry air under the existing conditions. Record the temperature and pressure. By means of the gas laws calculate the density under standard conditions, viz., 0° C. and 76 cm. of mercury. Calculate the density of the moist air in the room. From this value and the dimensions of the laboratory compute the mass of moist air in the laboratory.

B. (If weather permits, it is advisable to perform the remainder of this experiment in the outside air.) Observe the readings of a wet and dry bulb thermometer and from the tables or charts find the relative humidity, dew point, and the absolute humidity.

C. Determine the dew point experimentally by the evaporation of ether in a polished metal vessel and observing the temperature at which the dew begins to form on the sides of the vessel. A simple microscope will be found useful in observing the formation of dew. Do not breathe on the metal vessel. Having found the dew point in this way, from the tables find the saturation vapor pressure of water existing in the vicinity, and also the maximum saturation vapor pressure corresponding to the temperature of the air in the vicinity. Calculate the relative humidity.

12. VAPOR PRESSURE

Read Caswell's *An Outline of Physics*, pp. 102–109, 113–115.

The Principle of the Experiment. The saturated vapor pressure of a liquid increases exponentially with the temperature. The vapor pressure at the boiling point is equal to the atmospheric pressure. In this experiment the student is expected to obtain a vapor pressure curve for one liquid and to compare the vapor pressures of a number of liquids and liquid mixtures.

Regnault found that the vapor pressure of a mixture of two or more volatile liquids is equal to the sum of the vapor pressures of the constituents, provided they do not dissolve each other. He also found that in the case of liquids which do dissolve each other the vapor pressure of the mixture is less than the sum of the vapor pressures of its constituents.

Work to be Done. A. The "boiling-point tube" is a U-shaped tube closed at one end, filled with mercury and having a small quantity of some volatile liquid entrapped in the closed end. Place the tube in a large test tube filled with water deep enough to cover the closed end of the tube. At the same time read the positions of the mercury surfaces in both sides of the U-tube. Record the barometric pressure. Warm the tube and repeat the readings at intervals of about 5° C. until the mercury surface in the closed end of the tube is within a cm. or so of the bend in the tube. CAUTION. Be sure to take the boiling-point tube out of the test tube before the mercury reaches the bottom of the closed arm, otherwise disastrous results may follow. Obtain a similar set of readings with decreasing temperatures.

The lower end of a barometer tube is immersed in an iron cistern filled with mercury. A small amount of the liquid used in the boiling-point tube is on top of the mercury in the barometer tube and is surrounded by a water jacket which may be filled with water at about 40° C. A small vapor bubble will form above the mercury if the height of the barometer tube is properly adjusted. The vapor pressure in the bubble is equal to the difference between the atmospheric pressure and the height of the mercury in the barometer tube you are using. N.B. In determining the mercury levels one should always add the height of a mercury column which is equivalent to the height of the liquid resting on the mercury.

Plot vapor pressures as ordinates and temperatures as abscissæ including the value of the vapor pressure of the liquid at room temperature as found from one of the tubes mentioned in the next paragraph. What temperature as shown by your plot corresponds to 76 cm. pressure? Is this the boiling-point? Why? What liquid did you have?

B. Vapor pressure tubes similar to ordinary barometer tubes are mounted in sets of four, one of which contains no liquid over the mercury. The others contain small quantities of a number of liquids and are suitably labelled. In some of the tubes there is a mixture of two liquids. Show that the difference in height between the mercury columns in the latter tubes and the first-mentioned equals the vapor pressures of the contained liquids. Determine the vapor pressures of as many liquids as are available. Compare with the vapor pressures of the pure liquids the vapor pressures of as many of their mixtures as you can. If the vapor pressure of any mixture is not equal to the sum of the separate vapor pressures, account for the apparent discrepancy. Record room temperature. Tabulate your data.

13. CHANGE OF STATE—SOLID TO LIQUID

Read Caswell's *An Outline of Physics*, pp. 94–100, 130–131.

The Principle of the Experiment. One of the effects produced by imparting heat to a body is to change it from the solid to the liquid state, or from the liquid to the gaseous state. The temperature at which the change occurs depends upon the nature of the substance and the pressure to which it is subjected. In the case of some substances the melting point is sharply defined while other substances have no sharply defined melting point.

A definite amount of heat is required to melt a unit mass of any substance. This amount of heat is called the latent heat of fusion of the substance. The calorimetric equation for this case is similar to that for the latent heat of vaporization given in Experiment 15.

Work to be Done. A. The ends of a block of ice are supported in such a way that a heavy weight may be supported by a loop of wire passing over the middle of the block. Suspend a weight in this manner and note the appearance of the block and the wire from time to time. If the ice is cut, does it fall apart? Why? What is the effect of pressure on the melting point? Does ice contract or expand in melting? Is there any relation between this fact and the phenomenon just observed?

B. Support a test tube containing napthaline, paraffin, or beeswax in a beaker of water on a ring stand and melt the solid by heating the water. When the substance is completely liquefied, the thermometer should be inserted, if not previously in place, through a one-hole stopper. With the stopper firmly in the test tube, the bulb of the thermometer entirely covered by the melted material, and the whole safely above the melting point, remove the burner and the beaker of water and let the tube cool in the air without being disturbed in any way. Take readings of the temperature every half minute, tabulate and plot these readings as ordinates and the time as abscissæ. Note any peculiarities of the curve. Does it indicate a definite temperature of solidification? Does it indicate whether a substance gives out or absorbs heat during solidification?

C. Weigh the inner vessel of the calorimeter. Then fill it about two-thirds full of water and heat it to about 25 Centigrade degrees above room temperature. Prepare a piece of clear ice

about the size of a hen's egg. Weigh the water, replace the inner vessel in the calorimeter jacket, and at once thoroughly stir the water and take its temperature. Carefully slide the piece of ice, which has just been made as dry as possible with a towel, down the thermometer into the water. Stir continuously until the ice disappears, and then read the thermometer. It should be a few degrees below room temperature. If it is above room temperature, repeat the experiment, using a larger piece of ice or a smaller amount of water. Determine the mass of ice melted by weighing the inner cup of the calorimeter and its contents again. Calculate the amount of the heat required to melt one gram of ice without changing its temperature using an equation patterned after the one given in Experiment 15.

14. SPECIFIC HEAT BY THE METHOD OF MIXTURES

Read Caswell's *An Outline of Physics*, pp. 123–129.

Preliminary Exercise. Partially fill three similar glass beakers with equal masses of three different liquids. Use water for one of the liquids. One of the others may be a vegetable oil, such as olive oil or turpentine, or glycerine. The third may be a mineral oil, such as kerosene or some kind of machine oil. Avoid the use of liquids having highly inflammable vapors such as gasoline. Determine the temperatures of the liquids with a thermometer. Then place the beaker containing water over a Bunsen flame until its temperature rises about 20° C. Note its final temperature and also the time it was being heated. Then place each of the other beakers in turn over the flame for the same length of time that the water-filled beaker was over it, being careful to see that the flame burns in the same way and that the beakers are in the same position relative to the flame. Note the changes in temperatures in each case. The differences in the temperature changes that you observe with the different liquids evidently depend upon some property which is a characteristic of each liquid. This characteristic is the specific heat of the liquid.

The Principle of the Experiment. Specific heat is defined in such a way that the heat, H, required to change the temperature of a mass m of the substance through t degrees is given by

$$H = mst,$$

where s = specific heat. The heat capacity (or thermal capacity) is given simply by the product ms. In the determination of specific heat by the method of mixtures, one body, or group of bodies, is cooling down and another group is warming up. This process will continue until they are all at the same temperature. The heat lost by the body or bodies cooling down is equal to that gained by those warming up.

The calorimeter consists of an outer and an inner cup, the inner cup being supported by a ring of some heat-insulating material resting upon the outer cup. The space between the cups should be kept clean and dry. The cups ordinarily have a bright nickel surface to prevent loss of heat by radiation. Some water is placed in the inner cup, preferably at a temperature below that of the room, and its temperature determined with a

thermometer. The substance whose specific heat is to be determined is heated to a temperature above that of the room, its temperature is observed, it is then poured into the water and the resulting temperature observed. From the principle mentioned above we find that

$$m_h s_h (t_h - t) = (m_w + e)(t - t_w),$$

where e is the water equivalent of the calorimeter, m_w is the mass of the water, m_h = mass of substance, t_w and t_h the corresponding initial temperatures, t = final temperature, and s_h the specific heat of the substance.

Work to be Done. A. Determine the heat capacity of the inner cup and stirrer of the calorimeter and the specific heat of the metal of which they are made as follows: Weigh the inner cup and stirrer and then pour about 100 cc. of very cold water into it and weigh again. Place a thermometer graduated to tenths of a degree in the water and as soon as its temperature becomes steady read the temperature and then pour in about another 100 cc. of water at about 35 or 40° C., the temperature of the warm water having been previously observed. Stir gently and read the temperature again as soon as it becomes steady. Weigh the cup and its contents again and calculate the thermal capacity, or water equivalent, of the cup, stirrer and thermometer. Immerse the bulb of the thermometer in a glass graduate and determine its volume. From the density of mercury (13.6 gm/cc.) and its specific heat (0.031) calculate its thermal capacity. Calculate the thermal capacity of the cup and stirrer. Repeat two or three times and take the average value. If the cup and stirrer are made of the same material, from their combined mass previously obtained, calculate the specific heat of the material.

B. Fill the cup about half full of water almost at 0° C. and weigh again. Heat about half the mass of kerosene that you have of water in a vessel surrounded by boiling water and from the barometric pressure determine the boiling point of the water. Keep the kerosene in the water bath until it is certainly at the temperature of the boiling water. Stirring will hasten the process. Read the temperature of the cold water and then as quickly as possible remove the kerosene from the water bath and pour into the calorimeter. Stir well and read the temperature of the mixture. This temperature ought to be close to room temperature, hence radiations and similar corrections may be neglected. Weigh the cup and its contents and calculate the specific heat of kerosene. Make at least two determinations.

15. HEAT OF VAPORIZATION OF WATER

Read Caswell's *An Outline of Physics*, pp. 132–133.

Preliminary Exercise. Pour a few drops of ether into the hand and note the sensation as the liquid evaporates. Repeat using alcohol, which has a higher boiling point and does not evaporate as rapidly as ether. Repeat a third time with water. Place some water in a vessel over the flame of a Bunsen burner and note that the liquid first becomes warmer, but after it begins to boil its temperature no longer rises, and the liquid boils away. What conclusions do you draw from these experiments?

The Principle of the Experiment. If heat is absorbed when a liquid evaporates, we should expect that heat will be liberated when it condenses. We should also expect that the amount of heat associated with such changes is proportional to the amount of the substance evaporated or condensed.

Let dry steam be conducted into a calorimeter nearly full of water, which is initially several degrees below room temperature, until the temperature of the water is as much above room temperature as it was below at the first. The amount of heat given out by the steam in condensing and by the resulting water in cooling to the final temperature of the water in the calorimeter raises the temperature of the calorimeter and its contents from their initial temperature to the final temperature of the water in the calorimeter. Applying the calorimetric principle to this case, we have

$$mL + m(t_s - t) = (m_w + e_c)(t - t_w), \qquad (1)$$

where m = mass of steam condensed, L = latent heat of vaporization, t_s = temperature of steam, i.e., boiling point of water, t = final temperature of water in the calorimeter, m_w = original mass of water in the calorimeter, e_c = thermal capacity, or water equivalent, of the calorimeter, thermometer, etc., and t_w = initial temperature of the water in the calorimeter.

By having the final temperature of the water in the calorimeter as much above room temperature as the initial temperature was below, the heat received from the surroundings should equal that lost to the surroundings.

Work to be Done. A. Fill the inner cup of a calorimeter, such as was used in the determination of specific heat by the

method of mixtures, about two-thirds full of water at about 10° C. Make the necessary weighings for the determination of m_w and e_c.

Pass a gently flowing stream of steam into the water from a steam calorimeter. In order to prevent water being carried into the calorimeter by the steam, the latter may be passed through a water trap placed directly over the calorimeter and as close to it as possible. The outlet tube of the water trap should extend nearly to the bottom of the water in the calorimeter. This outlet tube should not be inserted into the calorimeter until after steam has been issuing from it for some time and there is no further tendency for water to collect on the end of it. If all the connections between the steam generator and the calorimeter are wrapped with cotton, better results are assured.

In the event of no water trap being available, the delivery tube conducting the steam from the generator to the calorimeter should slope upward from the generator so that any water which may consense *en route* may flow back into the generator. Care must be taken to avoid having water collect at any point in this connecting tube, because if it should completely fill the tube at any point, the steam may drive the water thus collected over into the calorimeter.

When all is ready to begin passing steam into the water in the calorimeter, take the temperature of the water and then quickly insert the outlet tube of the water trap into the water in the calorimeter.

After the temperature of the water has been raised a sufficient amount, stop the flow of steam and take the final temperature of the water. See part B. The thermometer may be kept in the water throughout the experiment, but the steam should not be allowed to strike it, as the thermometer reading will then be very much too high. The water should be well stirred to be certain that the final temperature as given by the thermometer is the true temperature of the water. Weigh the inner cup of the calorimeter and contents and determine the mass of steam condensed. Record the barometric reading and the temperature of the boiling point, and with the aid of equation (1) calculate the latent heat of steam at the observed boiling point. Check this value with the values given in tables.

Make at least two concordant determinations of L.

B. Owing to the way in which heat is supplied to the water, the temperature where the steam enters is apt to be much higher than it is elsewhere in the cup. Consequently a few moments will elapse after the flow of steam has ceased before the temperature

is uniform throughout. In this interval of time, some heat may be lost to the surroundings, and so the final observed temperature may be too low. If the calorimeter is well insulated for heat, this loss is likely to be small. To find out what it is, the temperature of the water may be read at intervals of 15 sec. beginning with the instant the steam was cut off. With the observed temperatures as ordinates and times as abscissæ, plot a curve. After the first few intervals of time this curve should slope downward toward the time-axis. Prolong this part of the curve back until it intersects the temperature-axis, and the point of intersection will give the correct final temperature to be used in part A. Explain.

16A. HEAT OF COMBUSTION OF THE GAS USED IN THE LABORATORY

Read Caswell's *An Outline of Physics*, pp. 123–125, 133–136.

The Principle of the Experiment. The process of combustion consists in bringing about a chemical reaction between the atoms or molecules of the fuel and the oxygen of the air with an accompanying evolution of heat. Combustion is not complete unless as much oxygen as possible is combined with the constituents of the fuel.

The apparatus is known as a Junker's calorimeter. It consists of a calorimeter which entirely surrounds the flame of a Bunsen burner. The calorimeter is of the continuous-flow type in which a steady stream of water enters the calorimeter by the lower pipe, and leaves by the upper. The flow of water is regulated by raising or lowering a constant level overflow cup having two orifices in the bottom and an overflow pipe. One of the orifices is connected to the intake pipe of the calorimeter, the other to the water faucet. The faucet is adjusted so that a small stream of water flows out through the overflow pipe. Thermometers, reading to 50° C., are inserted in the intake and outlet pipes of the calorimeter. The Bunsen burner should be adjusted so as to mix as much air as possible with the gas without causing the flame to go out. The burner is connected to the gas mains through a gas gauge which reads the volume of gas burned per hour.

Work to be Done. Start a stream of water through the calorimeter and light the burner. Then adjust the height of the cup so that, after the thermometer readings have become stationary, the thermometer in the outlet pipe is about 30° C. above that in the intake pipe. Regulate the burner for most complete combustion taking care to see that no more heat is lost to the surroundings than can possibly be avoided. Avoid having too large a flame or having it too low in the cavity in the calorimeter, and be sure it has plenty of air. After the thermometer readings have been stationary for a few minutes, record these readings and also the readings of the gas gauge. Then collect a liter or so of the water issuing from the outlet pipe of the calorimeter, recording the times at which you began collecting and stopped collecting the

water. Determine the mass of the water by weighing. Compute the mass of the water, m, which passes through the calorimeter per second, and also the volume of gas burned per second. Let this volume be V. If the thermometer readings are t_1 and t_2, the heat of combustion of the gas is given by the equation

$$H = m(t_1 - t_2)/V.$$

Make at least two concordant determinations of H.

16B. HEAT VALUE OF COMMERCIAL GAS UNDER NORMAL CONDITIONS OF USE

Read Caswell's *An Outline of Physics*, pp. 123–125, 133–136.

The Principle of the Experiment. The heat of combustion of the gas used in the laboratory may be found in Experiment 16A, but in that experiment the combustion is complete and no heat is lost, or at least these are the conditions which the experimenter strives to obtain. In actual practice, however, combustion may not be complete and a considerable fraction of the total heat produced is not usefully employed. In this experiment the student will attempt to duplicate the conditions prevailing in a well-regulated gas range.

Work to be Done. A. Start one of the gas burners in a gas plate and regulate as you would for cooking. Weigh a nickel-plated copper tea kettle. Then fill it about half-full of tap water and weigh again. Take the temperature of the water and note the reading of the gas meter at the instant the kettle is placed over the fire. If the gas meter does not read the volume of gas directly, note the time at which the kettle was placed over the fire as well. Again note the reading of the gas meter, and, if necessary, the time when the temperature of the water has risen about 50° C.

From the mass of the water heated and its change in temperature calculate the amount of heat received by the water, and from this result and the volume of the gas used compute the amount of heat usefully employed per unit volume of the gas used. It may be desirable to use the British system of units throughout.

Repeat, using an enamelled kettle instead of the copper kettle, and compare results.

B. Repeat A, using the copper kettle, but having a stove lid or a heavy sheet of iron over the flame under the kettle. The stove lid may be over the fire for a minute or two before the kettle is placed upon it.

Then repeat the experiment again, using an asbestos plate instead of the stove lid under the kettle.

Compare these results with those found in part A and draw the obvious conclusions.

C. From your results, using the most economical method, find the cost of heating 100 gallons of water from the temperature of tap water to the boiling-point. Use gas prices in your own vicinity.

17A. HEAT CONDUCTIVITY OF A GOOD CONDUCTOR

Read Caswell's *An Outline of Physics*, pp. 145–147.

Preliminary Exercise. Place a beaker containing a known amount of water over a Bunsen burner, or other source of heat, with a sheet of copper, or other metal, between the beaker and the flame, and note the length of time required for the temperature of the water to rise, say, 10° C. Repeat, using a sheet of asbestos of approximately the same thickness between the beaker and the flame. Evidently the amount of heat entering the water in a given time depends upon the nature of the material interposed between it and the source of heat.

The Principle of the Experiment. In text-books of physics it it is shown that the amount of heat H which passes through a layer of any substance, which is L centimeters thick, in T seconds is given by

$$H = \frac{TAK(t_1 - t_2)}{L}, \tag{1}$$

where t_1 is the temperature of the hotter side in degrees Centigrade, and t_2 is the temperature of the colder side, A is the cross-section of the layer perpendicular to the direction of flow of heat in square centimeters, and K is a constant which is characteristic of the material, called the heat conductivity.

In the apparatus used, the heat flows lengthwise of a rod of copper of some other metal which is jacketed with felt to prevent loss of heat to the surroundings. Two small holes are drilled almost through the rod at a distance apart equal to L cm. Into these holes, thermometer bulbs, which fit snugly, are inserted. To make better thermal contact a drop or two of water may be put into each hole. The readings of these thermometers are t_1 and t_2. Live steam is passed through a chamber surrounding one end of the rod, and a steady stream of tap-water is passed through a second chamber at the other end. The latter chamber is provided with receptacles for two thermometers, which indicate the temperatures of the entering and escaping water. These temperatures are t_3 and t_4. The flow of water is regulated by raising or lowering a constant level overflow cup having two orifices in the bottom and an overflow pipe. One of the orifices is connected to the intake pipe of the water chamber, the other to

the water faucet. The faucet is adjusted so that a small stream of water flows into the sink through the overflow pipe. If a mass of water m flows through the chamber in the time T, then

$$H = m(t_4 - t_3), \qquad \text{and} \qquad K = Lm(t_4 - t_3)/TA(t_1 - t_2).$$

Work to be Done. Start a stream of steam through the steam chamber and a stream of water through the water chamber, and adjust the height of the overflow cup so that, after the thermometer headings have become stationary, the temperature of the water escaping from the water chamber is about 30° C. above that of the water entering. After all four thermometer readings have been stationary for a few minutes, record the readings, also the boiling point. Measure the distance L and the diameter of the rod, and calculate the area A. Also determine the mass of water, m, flowing through the water chamber in the time T. Calculate the value of K.

Make at least two concordant determinations of K. How closely does your average value check with that given in the tables?

17B. HEAT CONDUCTIVITY OF A POOR CONDUCTOR—GLASS

Read Caswell's *An Outline of Physics*, pp. 145–147.

Preliminary Exercise. If the student has not performed Experiment 17A he may perform the preliminary exercise of that experiment.

The Principle of the Experiment. Read the first part of this section in Experiment 17A.

Glass is a poor conductor of heat so a large value of A is desirable, and the small value of L.

In the apparatus used the heat flows inward through the walls of a glass tube, thus giving a large area through which the heat is propagated, but a short distance for it to travel. This tube is surrounded by a larger metal, or glass, tube and live steam is passed through the intervening space. To the ends of the glass tube being tested, T-shaped tubes are attached, and a stream of tap water is passed into the former tube through one of the latter and out through the other. The tube should be tilted to that the water going through it is flowing uphill. In order to insure uniform heating of the tube, the water is forced to traverse it spirally by means of a strip of rubber wound spirally on a thin rod and inserted inside the tube. Thermometers are inserted in the T-shaped tubes, which indicate the temperatures of the entering and escaping water. These temperatures are t_3 and t_4. The flow of water is regulated by raising or lowering a constant level overflow cup having two orifices in the bottom and an overflow pipe as in Experiment 17A. One of these orifices is connected to the intake tube and the other to the water faucet. The faucet is adjusted so that a small stream of water flows out through the overflow pipe. If a mass of water m flows through the glass tube being tested in the time T,

$$H = m(t_4 - t_3) \qquad \text{and} \qquad K = Lm(t_4 - t_3)/TA(t_1 - t_2),$$

where t_1 is the boiling-point of water and t_2 is the mean of t_3 and t_4.

Work to be Done. Start a stream of steam through the outer space and a stream of water through the tube, and adjust the height of the cup so that, after the thermometer readings have become stationary, the escaping water is about 10° C. warmer

than that entering. Record these readings after they have become stationary, also the boiling-point. Determine the inner and outer radii, r_1 and r_2, respectively, of the tube under test, and the length, x, of the tube exposed to the water. Then,

$$A = \pi(r_1 + r_2)x, \qquad \text{and} \qquad L = r_2 - r_1.$$

Determine the mass of water m flowing through the tube in the time T and calculate the value of K.

Make at least two concordant determinations of K. How closely does your average value check with that given in the tables?

18. SPECIFIC HEAT OF A LIQUID BY THE METHOD OF COOLING

Read Caswell's *An Outline of Physics*, pp. 127–129 and 152–154.

Preliminary Exercise. If the student has not already performed Experiment 14, he may perform the preliminary exercise of that experiment.

The Principle of the Experiment. According to Newton's law of cooling, the amount of heat lost by a given surface in a unit of time depends only upon the character and area of the surface and the difference of temperature between the body and its surroundings. If t_1 = time required for a body having a thermal capacity (or water equivalent) = e_1 to cool through $\theta°$ C., and if t_2 = time required for a body having a thermal capacity = e_2, but its surface identical in area and character with that of the first body, to cool through the same range of temperature, then

$$e_1/e_2 = t_1/t_2.$$

It is important that the surroundings be at the same temperature in both cases.

Work to be Done. A. Determine the specific heat of a liquid such as alcohol, olive-oil, turpentine, or kerosene in the following manner. The space between the inner and outer cups of a calorimeter is filled with a mixture of melting ice and water. A nickel cup containing a liquid whose specific heat is to be determined is tightly closed with a stopper through which a thermometer is inserted so that the bulb is in the liquid. This nickel cup is suspended inside of the inner cup of the calorimeter in such a way that it is completely insulated from it. In case the nickel cup is not available, almost any small metal vessel or glass test tube will serve the purpose. The nickel cup should be filled with water at a temperature between 35 and 40° C. and its temperature observed at intervals of one minute until the temperature has fallen below 15° C. The thermal capacity of the cup and the immersed portion of the thermometer should be determined and also the mass of the liquid. For the method of computation of the thermal capacity see Experiment 14.

Empty out the water and fill the cup with the liquid whose specific heat is to be determined. Observe the time required for

its temperature to fall through the same range. Using temperatures as ordinates and times as abscissæ, plot the cooling curves for both the liquid and water on a sheet of rectangular cross-section paper, and from these curves determine the length of time required for each of these liquids to cool from 35 to 15° C. From the known values of the times of cooling and the thermal capacity of the cup and of the water, and the mass of the liquid whose specific heat is being determined, calculate the specific heat of the liquid.

B. Determine the specific heat of carbon bisulphide (CS_2) using the same method as part A. Since carbon bisulphide boils at about 46° C., be careful not to heat this liquid to a temperature any higher than is necessary. Inasmuch as the vapor is highly inflammable it would be well to warm the CS_2 by dipping the nickel cup quickly into water at about 40° C. Use the cooling curve for water from part A. Can you determine the specific heat of the carbon bisulphide without raising its temperature to the 35° C. specified in part A?

19. ACCELERATION, FORCE, AND MASS

Read Caswell's *An Outline of Physics*, pp. 175–189.

The Principle of the Experiment. According to Newton's second law of motion, whenever a force acts upon a body it produces an acceleration in the motion of the body which is proportional to the force, which is in the same direction as the force, and which is inversely proportional to the mass of the body.

If the force acting upon a body is constant, the acceleration should be constant. The acceleration of a body is determined directly by ascertaining the distances traveled by the body in successive equal intervals of time. If d = distance traveled during an interval of time, and t = time, the average speed during the interval is given by $v = d/t$. If v' and v'' be the average speeds during two successive intervals of time, the average acceleration is given by $a = (v'' - v')/t$. If the acceleration is constant, the value of a calculated from any two successive intervals of time should be the same as that calculated from any other two successive intervals, within the limits of experimental error. By taking the average of the values of a calculated from a series of intervals, the experimental error is greatly reduced.

A variety of instruments are used for the determination of the acceleration of bodies moving in straight lines under the action of known forces, and they all depend upon the foregoing principle. For example, an electrically-maintained tuning fork is allowed to fall between two uprights, and as it falls a stylus attached to one prong of the fork traces a wavy line on a sheet of glass which has been covered with a thin layer of cornstarch, Bon Ami, whiting or lampblack mixed with alcohol, or which has been smoked. Usually the interval of time chosen is that required for the fork to make 10 complete vibrations. All distances are measured by laying a meter stick beside the trace with its zero end at the point where the stylus was when the fork began to fall, and reading the positions of the stylus at the end of 10, 20, 30, 40, . . . complete vibrations of the fork, i.e., waves in the trace.

A narrow strip of paper may be attached to the falling object and a stationary vibrating brush may paint a wavy trace upon it. An electric spark may puncture the strip of paper at regular time intervals, or a rotating blade may cut the edge of it.

The distances having been determined and the interval of time being known, data may be conveniently arranged as shown in the accompanying table.

Interval of time $t =$ sec.	*Number of intervals $= n$*					
	1	2	3	4	5	6
Total distance from starting point $= s$	....	....	....	....	....	....
Distance during interval $= d = s_n - s_{(n-1)}$	....	....	....	....	....	....
Average speed $= v = d/t$	....	....	....	....	....	....
Average acceleration $= a = (v_n - v_{(n-1)})/t$	....	....	....	....	....	....
Average acceleration for whole trace $=$ cm./sec.^{2}	....	....	....	....	....	....

Whenever it is desired to obtain the acceleration when the force acting is not the weight of the objects being accelerated, some form of Atwood's machine is commonly employed. The falling tuning fork, mentioned above, may be used by running a cord from the carriage that carries the fork over a pulley attached to the top of the uprights and suspending from the other end another object which does not quite counterbalance the fork and its carriage. One of the most satisfactory types is Cussons' Atwood's machine. This consists of a light pulley supported by ball bearings over which runs a paper tape carrying equal loads at its ends. A similar piece of tape hangs in a loop from the lower sides of the two loads, so that the two loads are exactly counterpoised in any position. A trace is made upon the upper tape by an inked brush which is attached to a steel vibrator. A rider is placed upon one of the loads, which then begins to fall. The mass set in motion is the mass of the loads, the tape, the rider, and the equivalent mass of the pulley.

Work to be Done. A. Using the apparatus with which you are provided, make three independent determinations of the acceleration of a body falling freely under the action of the force of gravity. If the values thus obtained for the acceleration of gravity do not agree within the limits of probable experimental error, make additional determinations until you feel satisfied that your results are as good as can be expected from the apparatus you are using.

If the mean of your determinations differs appreciably from the accepted value of the acceleration of gravity in your locality, see if you can account for the discrepancy.

B. If Cussons' apparatus is available it is to be used in parts B and C of this experiment. If not, the following instructions must be interpreted so as to be appropriate for the apparatus employed.

Using 250 gm. weights for the loads, and a 5 gm. weight for the rider, determine the acceleration. The acceleration observed is too small, owing to friction. Determine the negative acceleration due to friction by removing the rider and starting the bodies by hand and calculating the acceleration as before. Add this result to the observed accelerations in parts B and C.

Repeat, using larger weights, say 350 or 400 gm., but the same rider. The force producing the acceleration is constant, viz., the weight of the rider. Using the equivalent mass of the pulley furnished by the instructor, check the law that the acceleration is inversely proportional to the mass.

C. Beginning with loads of about 350 or 400 grams on both sides, transfer part of one load to the other one. The accelerating force will then be twice the weight of the load transferred. Transfer 5 gm. and calculate the resulting acceleration. Then transfer 10 gm. and repeat. Again using the equivalent mass of the pulley check the law that the acceleration is directly proportional to the force.

D. Plot the total distances (s) obtained in part A on log-log cross-section paper as ordinates and times (t) as abscissas. Draw the straight line which best represents your results, and assuming that $s = \frac{1}{2}gt^n$, where g = acceleration of gravity, and n = some power of t, find g and n. How nearly does this value agree with that obtained for g in part A? How near is the value of n to 2?

20. A STUDY OF THE PERFORMANCE OF A WATER MOTOR

Read Caswell's *An Outline of Physics*, pp. 195–197.

The Principle of the Experiment. It is a well-known fact that the efficiency of any kind of motor, i.e., the ratio of the work which it will do to the energy which it consumes, depends upon the speed at which it operates. Obviously, a motor which is so heavily loaded that it cannot move is not doing any work, and so its efficiency is zero. Likewise, a motor which is running idle is not doing any work, yet it is consuming energy, and so its efficiency is zero in this case also. At some intermediate speed it will have a maximum efficiency. In this experiment we shall endeavor to determine the efficiency of a water motor throughout the entire range of its possible speeds.

The apparatus used consists of a water motor which is attached to the water mains, a pressure gauge being inserted between the faucet and the motor and as close as possible to the latter. A belt passes over the pulley and is attached to two spring balances which can be adjusted so as to vary the tension in the belt. A speed counter is provided.

If we denote the tensions in the two sides of the belt by F_1 and F_2, the circumference of the pulley by c, and the number of revolutions by n, the work done by the motor is given by

$$W = (F_1 - F_2)cn. \tag{1}$$

If P is the pressure and V the volume of the water which passes through the motor, the energy lost by the water is PV, and we have

$$\text{Efficiency of motor} = (F_1 - F_2)cn/PV. \tag{2}$$

Work to be Done. A. Connect the motor to the water mains through a short piece of hose and open the valve until the pressure is nearly as great as the pressure gauge will read. Throughout the experiment keep the pressure as nearly constant as possible. Adjust the spring balances so that the motor runs very slowly. Observe the difference in tensions in the belt. Using this as a guide, regulate the tensions so as to obtain three or four different speeds between zero and the maximum when the motor is running

idle. Make a complete set of observations for each of these speeds. The following form of tabulation is suggested, the blank spaces being filled in with names of units in which your various instruments are calibrated.

Trials

	1st	2nd	3rd	4th	5th
Tension on right in	....	....	....	....	....
Tension on left in	....	....	....	....	....
Circumference of pulley in	....	....	....	....	....
Number of revolutions........	....	....	....	....	....
Pressure in .... per sq.	....	....	....	....	....
Weight of water in	....	....	....	....	....
Time of beginning in h. m. s........	....	....	....	....	....
" " end " " " "	....	....	....	....	....

Make the necessary calculations, reducing all quantities to units of the same system, and record results thus:

Difference in tensions in dynes........	....	....	....	....	....
Relative movement of belt and pulley in cm........	....	....	....	....	....
Work done in joules........	....	....	....	....	....
Pressure in dynes per sq. cm........	....	....	....	....	....
Volume of water in cc........	....	....	....	....	....
Energy input in joules........	....	....	....	....	....
Efficiency in per cent........	....	....	....	....	....
Time interval in seconds........	....	....	....	....	....
Speed in rev. per sec........	....	....	....	....	....
Power in watts........	....	....	....	....	....

B. Plot efficiencies as ordinates and speeds as abscissæ and from your curve determine the maximum efficiency in per cent and the speed corresponding to it. How does this speed compare with the speed when the motor was running idle?

21. MECHANICAL EQUIVALENT OF HEAT

Read Caswell's *An Outline of Physics*, pp. 215–218.

Preliminary Exercise. Rub your hands together very briskly for a minute or two and note the heating effect produced. Using a fire syringe set a piece of tinder on fire through the heat due to the compression of the air. A similar effect may be produced by an auto or bicycle pump, which becomes warm when used to inflate a tire. Tyndall's friction cylinder consists of a hollow brass tube which is attached to a rotator. Partially fill the cylinder with alcohol or ether and close it with a tightly-fitting stopper. Rotate the cylinder rapidly between the jaws of a hand friction clamp lined with wood. The liquid may be made to boil and the vapor pressure will become great enough to expel the stopper.

The Principle of the Experiment. All frictional processes result in the production of heat. According to the first law of thermodynamics, whenever mechanical energy is transformed into heat, or whenever heat is transformed into mechanical energy, the heat energy is always equivalent to the mechanical energy. If we know the number of units of mechanical energy which are equal to one unit of heat energy, we can always determine the amount of heat which appears when mechanical energy is converted into heat, and vice versa. In symbols,

$$W = JH, \tag{1}$$

where W = mechanical energy expended, H = amount of heat produced, and J = mechanical equivalent of heat.

Heat is produced by friction between two brass cones, one of which fits snugly within the other, when the outer one is rotated relative to the inner. To the top of the inner cone a wooden disk is attached. A mass m is supported by a cord passing over a pulley and attached to the circumference of the disk.

If no slipping occurred between the cones, the mass m would be lifted a distance c against the force of gravity for each revolution of the outer cup, or a distance cn in n revolutions, where c = circumference of the wooden disk. So the mechanical

energy expended in rotating the outer cone through n revolutions is given by

$$W = Fd = mgcn, \tag{2}$$

where g is the acceleration of gravity.

The inner cone contains some water, a thermometer and stirrer. If K = water equivalent, or thermal capacity, of the two cones, water, thermometer, and stirrer, and the temperature rises from t_1 to t_2, the heat produced is given by

$$H = K(t_2 - t_1). \tag{3}$$

From equations (1), (2), and (3) we find that

$$J = mgcn/K(t_2 - t_1). \tag{4}$$

Work to be Done. Oil the surfaces of contact between the cones slightly, wiping off the surplus oil if necessary, until a weight of, say, 100 or 200 gm. can be supported when the apparatus is driven at a convenient speed. Part of the cord should always be kept wrapped around the disk so as to keep the torque constant. When starting and stopping, steady the disk with the hand to avoid jerking the apparatus.

Determine the thermal capacity of the cones, stirrer and thermometer, and after adjusting the friction as indicated above, partially fill the inner cone with water cooled to several degrees below room temperature. Determine the mass of the water and add its heat capacity to that of cones, etc. Record the room temperature. Observe the temperature of the water and then run the apparatus steadily, keeping water well stirred, until the temperature of the water is as much above room temperature as it was below originally. Record the number of revolutions of the outer cone. Obtain the final temperature by the method employed in Experiment 15. Using equation (4) calculate J. Make at least two concordant determinations.

What is the commonly accepted value of J? How does your average agree with this? Note possible sources of error in your experiment.

22. SERIES AND PARALLEL RESISTANCES

Read Caswell's *An Outline of Physics*, pp. 242–252.

Preliminary Exericse. Before attempting to connect electric appliances using large amounts of power to the laboratory power circuits, the student should become familiar with the art of tracing the path of the electricity through the various parts of the circuit. Electricity is not created or destroyed in the circuit, it simply flows around and around the circuit. In each of the following cases trace the path or paths of the electricity around the circuit.

With wires connect a dry cell, or storage cell, an electric bell, or buzzer, and a push-button in series, so as to ring the bell when the button is pressed. The push-button is one form of electric switch.

Introduce a second bell into the circuit so that both bells ring when the push-button is pressed. Is there any difference between the way in which the bells ring when they are in series or in parallel with each other? If so, why? How should they be connected for most satisfactory results?

Using two push-buttons arrange a circuit so that one bell will ring when one button is pressed and the other bell will ring when the other button is pressed.

Connect the battery and one bell in series with two three-way switches so that the bell may be rung from either switch. Single-pole double-throw switches will do. This is the sort of connection which is used when electric lights are turned on from either of two different places. Hint. Connect the switches by wires between the points of the switches not connected to the blades.

The Principle of the Experiment. In any part of an electric circuit in which electric energy is converted into heat (or through heating, into light), Ohm's law applies, viz., the product of the current in amperes and the resistance in ohms is equal to the difference in potential between its ends measured in volts. In symbols,

$$E = IR. \tag{1}$$

When a number of resistances, r_1, r_2, r_3, . . . , are connected in series, the total resistance, r, is given by

$$r = r_1 + r_2 + r_3 + \ . \ . \ . \ , \tag{2}$$

but if they are connected in parallel, the total resistance, r, may be found from the equation

$$\frac{1}{r} = \frac{1}{r_1} + \frac{1}{r_2} + \frac{1}{r_3} + \cdots \tag{3}$$

Work to be Done. **A.** As shown in Fig. 5, connect a source of current and switch (if the current is furnished from the laboratory mains, the switch on the end of the service cord is sufficient), a wire of fairly high resistance stretched over a meter stick, a rheostat for the control of the current, and a low reading ammeter in series. Connect up an additional side circuit containing a low-reading voltmeter. One end of this side circuit is permanently connected to one end of the meter wire, and the other may be touched at will to any point of this wire.

After connections have been approved by instructor, make tap contacts to see that the deflections of instruments are in the right direction, and of convenient amounts. Then close the main switch permanently. Record the reading of the ammeter. With the free end of the side circuit, make successive contacts on the meter wire at a series of points, say every 10 cm., recording the position on the wire and the corresponding deflection of the voltmeter, each time. Assuming that the resistance of the wire is proportional to its length, and that the indications of the voltmeter are proportional to the potential difference, show whether the experiment illustrates Ohm's law, and whether the law applies to portions of a circuit, such as different lengths of the same wire.

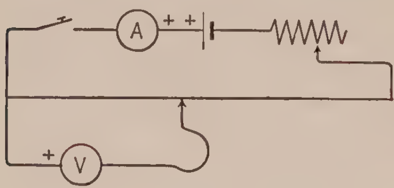


FIG. 5.

By means of the rheostat in the main line, change the current in that line. Record the ammeter reading. Then repeat the general procedure of the previous paragraph, using a smaller number of points. Do you find the same general relation between resistance and difference of potential as before? How has the change in the amount of the main current affected the readings? Is this change in accordance with Ohm's law?

From simultaneous readings of voltmeter and ammeter compute the resistances of five or six different lengths of the wire, using data with both amounts of current. From these results, compute the resistance of the wire per meter of length. Do the

different results agree closely? Record the average of these values.

B. Connect three or four resistances, an ammeter, and a double-pole, single throw switch in series with the terminals of a source of current. If 110-volt D.C. is available, incandescent lamps may be used as resistances. Connect a voltmeter to the terminals of one of the resistances and from its reading and that of the ammeter calculate its resistance. Do the same for each of the resistances separately. Then connect one terminal of the voltmeter to the first terminal of the first resistance and the other terminal of the voltmeter to the last terminal of the last resistance, and from the ammeter and voltmeter readings calculate the total resistance of all the resistances in series. Compare this result with the sum of the separate resistances.

C. Connect the resistances used in B in parallel and connect the ammeter so that the current in one resistance only passes through it. Connect the voltmeter to the common terminals of all the resistances. Read the ammeter and voltmeter and calculate the resistance of this one resistance. Then connect the ammeter so that the current through a second resistance only passes through it. Again calculate the resistance. Do this for the remaining resistances. If a sufficient number of ammeters are available, an ammeter may be put in series with each of the resistances. The results will then be more consistent.

Now connect the ammeter so that all the electricity flowing in all the resistances passes through it, and calculate the total resistance. Compare this result with that obtained from the separate resistances and equation (3).

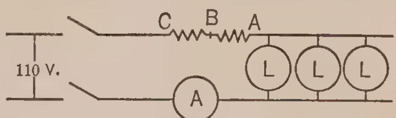


Fig. 6.

D. Connect a lamp-bank, an ammeter, and an imitation line resistance AB or AC, in series with a single-throw, double-pole switch, which is connected to the 110-volt D.C. mains, as shown in Fig. 6.

Attach two wires from the terminals of the lamps to those of a voltmeter. With the line resistance AB in the circuit, screw in the lamps one by one and record the effect. How does the voltage across the terminals of the lamp bank change as the number of lamps is increased? The total current? The current in each lamp? Explain. Tabulate your data.

Repeat using line resistance terminals A and C. Is the dimming as additional lamps are turned on greater or less than in the operations of the preceding paragraph? Why should it be so? Tabulate your data.

23. VARIATION OF RESISTANCE—THE WHEATSTONE BRIDGE

Read Caswell's *An Outline of Physics*, pp. 244–258.

The Principle of the Experiment. The units of voltage, current, and resistance having been suitably chosen, Ohm's law states that the voltage between two points in a conductor is equal to the product of the current between the two points and the resistance between them. If the current is measured by an ammeter and the voltage by a voltmeter, the resistance may be calculated from the equation $R = E/I$. If the ranges of the two instruments have been chosen so that the readings come about two-thirds the way up the scale, the current and voltage may be read to about 1/10th of one per cent. How accurate will the determination of the resistance be?

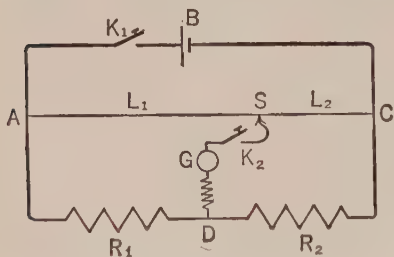


FIG. 7.—The Slide-Wire Wheatstone Bridge.

Whenever it is important to have more accurate determinations of a resistance than is possible with an ammeter and voltmeter, it is customary to use a Wheatstone bridge. The slide-wire form of this instrument, which is most easily comprehended is shown diagrammatically in Fig. 7. AC is a long, straight wire of uniform cross-section, mounted on a meter stick, and connected in parallel with the two resistances R_1 and R_2 which are in series. B represents a dry cell, a lead storage cell, or some other source of constant EMF, having an EMF between, say, 1.4 and 2.1 volts (the exact value is immaterial).

When the key K_1 is closed, electricity will flow through the wire AC and also through the two resistances. The electric pressure along the wire will vary continuously and at a uniform rate from A to C. At some point S in the wire the electric pressure will be exactly the same as the pressure at the point D, where the two resistances are connected. If a galvanometer, G, is connected between the points D and S, no electricity will flow through it, since the electric pressure is the same at D and S. Water

does not flow from a point at one level to another point at the same level. In practice, S is a sliding contact. By sliding the "slider" S to and fro on the wire, the point S may be located experimentally. The key, K_2, and the resistance in series with the galvanometer are inserted to protect the latter from too large currents.

Let the length of the wire between A and S be L_1 and that between S and C be L_2, and let the resistances of these portions be denoted, respectively, by R_3 and R_4. Since the wire is uniform,

$$R_3/R_4 = L_1/L_2.$$

Let I_w = current in the wire, and I_r = current in the resistances. Since the difference in electric pressure between A and S is the same as that between A and D, and since no electricity flows between D and S, it is obvious that

$$I_rR_1 = I_wR_3,$$

and similarly,

$$I_rR_2 = I_wR_4.$$

Whence,

$$\frac{R_1}{R_2} = \frac{R_3}{R_4}, \qquad \text{or} \qquad \frac{R_1}{R_2} = \frac{L_1}{L_2}.$$

Hence, if R_2 be known, R_1 can be calculated.

In the high-class forms of this instrument, the sections of the wire are replaced by resistances connected by simple ratios, such as 1: 1, 1: 10, 1: 100, 10: 100, and so on. These are then known as the "ratio arms" of the bridge. The resistance R_2 is varied after the ratio arms are set until no electricity flows through the galvanometer. (The student may be interested in showing that the positions of the battery and the galvanometer may be interchanged without affecting the setting of the instrument.)

Work to be Done. A. Connect a lamp socket in series with an ammeter and a double-pole, single-throw switch which is connected to the 110-volt D.C. circuit. With separate wires connect the terminals of a voltmeter of 150-volt range to the terminals of the lamp socket. Screw a carbon lamp into the socket. Make a tap contact to see that both instruments are connected in the right direction. Close the switch and read the instruments. Calculate R, the resistance, from the equation $E = IR$.

Repeat with the tungsten lamp.

B. Construct a slide-wire Wheatstone bridge circuit as shown in Fig. 7, using for R_2 a standard resistance box having a total

of, say, 1000 ohms. The resistance of the box is the sum of the numbers engraved opposite the places where the plugs have been removed. For R_1 insert a lamp socket containing one of the lamps used in part A. After all connections have been made as shown in the diagram but *before any keys have been closed* have the instructor examine your connections.

Adjust the resistance in the box R_2 so as to have about 200 ohms resistance. Close the key K_1. Then with the slider S about the middle of the wire AC make a "tap contact," i.e., close key K_2 for the briefest possible time, and note the direction and approximate magnitude of the swing of the galvanometer needle. Then move S a short distance either way and repeat the operation. If the swing is larger than before, try moving the slider the other way. Proceed in this way, endeavoring to find some place where it will not swing either way or will swing in the opposite direction. If the slider is too close to A, the galvanometer will swing in one direction, but if it is too close to C it will swing in the opposite direction. When the slider is situated at such a point that the galvanometer does not move when the key K_2 is closed, the "bridge" is said to be balanced and

$$R_1/R_2 = L_1/L_2.$$

Adjust the slider until no deflection is obtained and calculate the value of the unknown resistance, approximately. Adjust the resistance in the box to about this amount, and again adjust the slider. Calculate the resistance of the lamp from this setting.

Repeat using the other lamp that was used in the first part of the experiment.

C. How does the resistance of carbon vary with the temperature? The resistance of tungsten? Assuming that the temperature of the incandescent carbon lamp is 1800° C., and that of the tungsten 2500° C. calculate the temperature coefficients of resistance in both cases. N.B. The temperature coefficient of resistance is defined in exactly the same way that the temperature coefficients of linear and cubical expansion are defined.

D. Replace the lamp socket and lamp in part B by a selenium cell. Cover up the cell so that it is in the dark and measure its resistance. Then uncover it and allow the light from a powerful lamp to fall upon it and again measure its resistance. What do you find? Can you account for the phenomenon?

24. ELECTROMOTIVE FORCE AND POTENTIAL DIFFERENCE—THE POTENTIOMETER

Read Caswell's *An Outline of Physics*, pp. 252–260.

Preliminary Exercise. Connect a variable resistance, of 10 ohms or more, in series with a contact key to the terminals of a dry cell or storage cell. Also connect a low-range voltmeter to the terminals of the cell. Read the voltmeter when the key is open, and then with about 10 ohms resistance in the circuit close the key and read the voltmeter again. Repeat the latter operation a number of times, reducing the resistance about 2 ohms at a time until the resistance is reduced to 1 or 2 ohms.
Be careful not to reduce the resistance below one ohm.

Does the voltmeter reading depend upon the resistance in the circuit? If the EMF of a cell is a characteristic of that cell, is the voltmeter reading in any case the EMF of the cell? If not, what relation does it bear to the EMF? Can a voltmeter be used to determine the EMF of the cell? What percentage accuracy did you obtain in your voltmeter readings? Do you consider the voltmeter a satisfactory instrument for the precise determination of electromotive force?

The Principle of the Experiment. For precise determinations of EMF some form of potentiometer is generally used. Since the failure of a voltmeter to give results having a high percentage accuracy is due to the flow of electricity through the source of EMF and to the limits of the observer's powers in taking readings, the potentiometer is designed so the EMF to be determined is balanced by a known electric pressure, this pressure being known in volts from a calibration of the instrument in terms of the EMF of a "standard cell."

The potentiometer consists essentially of a long wire of high resistance in series with an adjustable resistance and a "working battery." By adjusting the resistance in the circuit the current can be varied and the fall of potential over any given length of the wire thus adjusted to any desired amount.

When another circuit is connected in parallel with any given portion of the potentiometer wire, there is a fall of potential in the parallel circuit equal to that in the given portion of the potentiometer wire. However, no current will flow into or out of the parallel circuit from the working battery if either of the following conditions is satisfied.

1st Condition. If there is a cell or other source of current in the parallel circuit, the EMF of which is equal to the fall of potential in the given portion of the potentiometer wire, the cell being so connected that it tends to send current ***in the opposite direction*** to the fall of potential due to the working battery.

2d Condition. If a part of the parallel circuit is made a part of another complete auxiliary circuit and sufficient current is sent through this part of the parallel circuit by the source employed in the above-mentioned auxiliary circuit to make the fall of potential in this part of the parallel circuit equal to and ***in the same direction*** as the fall of potential in the given portion of the potentiometer wire. The resistance of the part of the parallel circuit times the current through it must then be equal to the fall of potential in the potentiometer wire between the points where the parallel circuit is connected to it.

Work to be Done. A. ***Have an instructor examine your connections before closing any keys.*** Referring to Fig. 8, AC is the potentiometer wire, which is connected in series with an adjust-

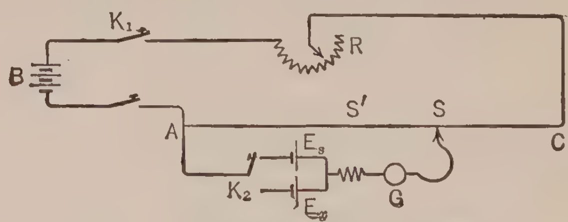


FIG. 8.—The Slide-Wire Potentiometer.

able resistance R, the double-pole single-throw switch K_1 and a working battery B of about three storage cells. The battery should be connected so that the current will flow through the potentiometer wire from A to C. By adjusting R the fall of potential along the wire AC can be made one volt per meter (or any other convenient amount). This is called "setting" the potentiometer, and is accomplished in the following manner. A circuit consisting of the single-pole double-throw switch K_2, a cell E_s of known EMF, i.e., a "standard" cell, a resistance (e.g., 1000 ohms) to protect the cell, and a galvanometer G, is connected in parallel with AS, S being a sliding contact on the wire AC. S is placed so that the length of wire AS in meters is numerically equal to the EMF of the cell E_s, which is connected to A through K_2.

A cell E_x, the EMF of which is to be determined, is connected

as shown. Having had your connections approved, put in all the resistance of R and close K_1 permanently. Place S at the proper point on the wire and close K_2 so as to form a circuit through E_s. Note the direction of the deflection of the galvanometer. If the deflection is small, the switch K_2 may be left closed, otherwise it should only be closed for an instant. Reduce the resistance in R and again close K_2. The deflection should now be less than before or else in the opposite direction. If this is not the case consult the instructor. Gradually increasing or decreasing as necessary, adjust the resistance in R until the galvanometer shows no deflection when K_2 is closed. The potentiometer is then said to be "set."

Having "set" the potentiometer, close K_2 so as to put E_x in the circuit instead of E_s. Following a procedure similar to that used in setting the potentiometer, but adjusting the position of S instead of the resistance in R, find the position of S for which there is no deflection of the galvanometer. When this is found, the distance between A and S in meters is equal to the EMF of E_x in volts. Why?

B. Connect a lamp socket containing an incandescent lamp in series with a "standard" one-ohm resistance and an ammeter to the 110-volt D.C. mains through a double-pole single-throw switch. Make a tap contact so as to determine the direction of the current through the ammeter and connect the ammeter so that it reads in the right direction. In the potentiometer circuit remove E_x and connect the wires formerly leading to it to the terminals of the standard ohm, in such a way that the current in the latter is from that terminal which is connected to K_2 to that one which is connected to the galvanometer G. ***Before closing switches have your connections approved by the instructor.*** Balance the galvanometer as before by adjusting the slider S. The distance AS in meters is numerically equal to the current through the standard ohm, i.e., through the lamp, in amperes.

C. With the apparatus used in part B see if you can devise a means of measuring an unknown resistance with the potentiometer.

25. ELECTRICAL EQUIVALENT OF HEAT—CONTINUOUS FLOW METHOD

Read Caswell's *An Outline of Physics,* pp. 264–267.

The Principle of the Experiment. The student is familiar with the fact that we use electric heaters for a variety of purposes and that the essential feature of an electric heater is a coil of resistance wire through which an electric current flows. In this experiment a measured current of electricity is sent through a coiled wire, which is inside a glass tube through which a steady current of water flows. The heat liberated by the wire warms the water, so that the water issuing from the one end of the tube is warmer than that entering the other end. In principle this experiment is similar to Experiment 16 A.

If m grams of water pass through the tube in T seconds, and if the temperature of the entering water is t_1 and that of the issuing water is t_2, the amount of heat supplied to the water by the electric current is

$$H = m(t_2 - t_1). \quad (1)$$

If the electric current is I and the potential difference between the two ends of the wire which is being heated is E, the electric energy supplied in T seconds is

$$W = EIT. \quad (2)$$

But, since $W = JH$,

$$J = EIT/m(t_2 - t_1) \quad (3)$$

Work to be Done. Place thermometers, reading to 50° C., in the T-tubes at the ends of the glass tube containing the resistance wire. Connect the heating coil in series with an ammeter, a suitable resistance, and the 110-volt D.C. mains, and connect a voltmeter across the terminals of the heating coil. ***Start the flow of water first and then start the electric current.*** Regulate the flow of water so that the temperature of the water issuing from the tube is about as much above room temperature as that of the entering water is below. The electric current and the current of water should both be maintained as constant as possible. After the thermometers have become steady read the ammeter and volt-

meter, and also read the thermometers. Collect the water issuing from the glass tube during a known length of time.

Use a current of about one ampere the first time, then repeat using a current of about 1.5 amperes. Calculate J for each case in joules per calorie. How closely do these values agree with each other and with the officially accepted value of J? How closely does the ratio of the values of the heat developed per second in the two cases agree with the ratio of the squares of the current?

26A. THERMOELECTRICITY

Read Caswell's *An Outline of Physics*, pp. 267–270.

The Principle of the Experiment. A thermo-couple or thermo-element, consists essentially of two wires of two different metals with their ends soldered or otherwise fastened together in good electrical contact. If the temperature of one of the junctions is higher than that of the other, a current will flow in the circuit, and the EMF giving rise to the current is called the thermo EMF. The current in the circuit will be proportional to the thermo EMF, provided the resistance of the circuit does not change. This current can be measured by connecting a galvanometer into the circuit as shown in Fig. 9. If the terminals of the galvanometer are not kept at the same temperature, an additional thermo EMF may be introduced into the circuit which will vitiate the results of the experiment. If the thermo-couple-galvanometer circuit is kept unaltered, and if the temperature of one of the junctions is kept constant, e.g., at 0° C., the apparatus may be calibrated so that the temperature of the second junction may be determined from the reading of the galvanometer. In fact the galvanometer scale may be made to read temperatures directly. Such an instrument is known as a thermoelectric pyrometer.

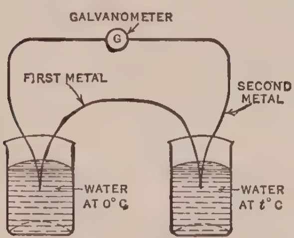


FIG. 9. — The Seebeck Effect. An Electric Current Flows When the Two Junctions Are Not at the Same Temperature.

Whenever electricity flows across a junction between two metals heat is either absorbed or liberated at the junction, the amount absorbed or liberated depending upon the strength and direction of the current, the nature of the metals, and the temperature of the junction. This is known as the Peltier effect.

Work to be Done. A. Connect a copper-constantan couple to a galvanometer as shown in Fig. 9. the copper being connected to the galvanometer. Immerse one junction in a mixture of water and melting ice and the other in boiling water. Press the key and read the deflection of the galvanometer. If the deflection of the galvanometer is less than half its scale, two, or more,

thermo-couples may be connected in series and the alternate junctions placed in the melting ice and in the boiling water. This will multiply the readings of the galvanometer and provide a more sensitive means of determining temperature.

Read the galvanometer deflection with one junction in the boiling water and the other in the ice, and also determine the temperature of the boiling point from the barometer reading. Then read the galvanometer deflections at intervals of about 10° C. down to 10° C., each time stirring the water thoroughly before taking the reading and observing the temperature at the same time with a good mercury thermometer.

On rectangular cross-section paper plot a curve using galvanometer readings as ordinates and temperatures of the warm junction as abscissæ.

Place the hot junction in a liquid whose temperature is not known, read the galvanometer, and from your curve determine the temperature of the liquid.

B. Connect your galvanometer, thermo-couple, a dry cell and a three-way key, or single-pole, double-throw switch, as shown in Fig. 10. Close the key so as to connect the galvanometer to the thermo-couple and if the two junctions are at the same temperature there will be no deflection of the galvanometer. If there is no such deflection, close the key so that the dry cell will send a current through the thermo-couple. At the end of one minute reverse the key so as to connect the galvanometer to the thermo-couple and note the galvanometer reading. Calculate the difference in temperature between the junctions of the thermo-couple at the instant it was connected to the galvanometer. Estimate the time the current would need to flow in order to give the maximum deflection of the galvanometer. Allow the current to flow for this length of time and read the galvanometer deflection. Is it smaller than you anticipated? If so, can you suggest a reason?

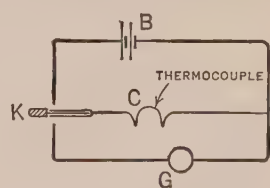


Fig. 10.—Illustrating the Peltier Effect.

C. Fill a copper vessel nearly full of boiling water and determine its temperature with your thermo-couple at intervals of one minute for five minutes, then at intervals of two minutes for the next ten minutes, and at intervals of three minutes for the next fifteen minutes. Plot a cooling curve for the water, using temperatures as ordinates and times as abscissæ. Can you justify the use of longer time intervals in the latter part than in the forepart of the experiment?

26B. THERMO ELECTROMOTIVE FORCE AND THERMOELECTRIC POWER

Read Caswell's *An Outline of Physics*, pp. 267–269.

The Principle of the Experiment. A thermo-couple, or thermo-element, consists essentially of two wires of two different metals with their ends soldered or otherwise fastened together in good electrical contact. If the temperature of one of the junctions is higher than that of the other, a current will flow around the circuit, and the EMF giving rise to the current is called the thermo EMF. The current in the circuit can be measured by connecting a galvanometer into the circuit as shown in Fig. 9, but care should be taken to see that the terminals of the galvanometer are at the same temperature. The EMF may be measured directly by means of a sufficiently sensitive potentiometer, at any temperature.

The student is advised to review the experiment on the simple slide-wire potentiometer before proceeding with this experiment. See Experiment 24.

In Fig. 11 *WB* is a "working battery" consisting of one or two storage cells, and k_1 is a switch to open this circuit. E is a

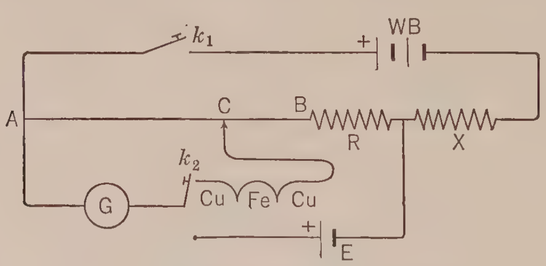


Fig. 11.—Thermoelectric Potentiometer.

"standard" cell whose EMF is known. *AB* is a straight wire one meter in length with a suitable resistance in parallel with it, so that the total resistance between *A* and *B* is one ohm. *R* and *X* are two standard resistance boxes having a total resistance of several hundred ohms each and adjustable in units as low as one ohm or perhaps 0.1 ohm. *G* is a galvanometer which can be connected either to the standard cell *E* or to the thermo-element, indicated by "Cu Fe Cu," by means of the single-pole double-

throw switch, or "three-way" key, k_2. The circuit through the thermo-element is completed through the slider C on the wire AB.

Work to be Done. A. To "set" the potentiometer: Adjust the resistance in R until it is one ohm less than 100 times the numerical value of the EMF of the standard cell E. Then the resistance AB plus R will be equal to 100 times the EMF of the cell E. Find out the approximate value of the EMF of the working battery, and adjust the resistance of X until

$$\frac{R}{R+X} \text{ is approximately equal to } \frac{\text{EMF of the cell } E}{\text{EMF of working battery}}.$$

Close k_1 and then close k_2 so as to put the galvanometer in series with the standard cell. k_2 should only be kept closed long enough to determine the direction of the deflection produced in the galvanometer. Adjust the resistance X until the galvanometer shows no deflection.

Show that when the potentiometer has been set in this way, the potential difference between A and B will be 0.01 volt per meter, or 0.00001 volt per mm.

You are supplied with a number of thermo-elements made from the same pair of metals, connected in series so that connections may be made to one, two, or more, couples. These thermo-elements are mounted on a frame so that alternate junctions are close together, thus forming two sets. The one set is placed in a bath of melting ice and the other in a water bath which is to be heated. The water bath should be kept well stirred and its temperature read by means of a 100° C. thermometer as nearly as possible at the instant that the thermo EMF is determined on the potentiometer. The thermo EMF of the thermo-element is obtained by closing the switch k_2 so as to put the galvanometer in series with the thermo-element and the slider C. The slider C is then adjusted so that there is no deflection of the galvanometer. The thermo EMF is then obtained from the distance AC. If more than one couple is used, the observed thermo EMF must be divided by the number of couples. It is advisable to use enough couples to bring the slider C well toward the end B of the meter wire AB.

Determine the thermo EMF with the water bath at approximately the following temperatures: 10°, 20°, 30°, 40°, 50°, 65°, 80°, boiling point, 80°, 65°, 50°, 40°, 30°, 20°, 10°, taken in order given.

Plot the observed thermo EMF's as ordinates and the temperatures as abscissæ, and draw a smooth curve through the origin

which best represents your plotted points. This is the thermo EMF curve for the two metals used. If log-log cross-section paper is used, this curve will be almost, if not exactly, a straight line.

B. From the thermo EMF curve determine the thermo EMF at intervals of 10° C., from 0° C. to 100° C. Calculate the thermoelectric power for 5° C., 15° C., and so on up to 95° C. N.B. This quantity in each case is equal to one-tenth of the thermo EMF for the corresponding ten-degree interval. Plot these values of the thermoelectric power on rectangular cross-section paper as ordinates and the mean temperature of the interval as abscissæ. Draw a smooth curve through the plotted points.

If the thermoelectric power curve is a straight line, it may be represented by an equation of the form

$$Q = A + Bt,$$

where Q is the thermoelectric power at any temperature t° C., A is the thermoelectric power at 0° C. and B is the increase in the thermoelectric power per °C. See if you can express your results by an equation of this form.

27. FIELDS OF FORCE

Read Caswell's *An Outline of Physics*, pp. 203–204, 281–284.

The Principle of the Experiment. The distribution of the lines of flow of heat in a solid, or of the lines of flow of electricity in a metallic or electrolytic conductor, or of the magnetic flux, or lines of force, in a magnetic field, is similar to the distribution of the lines of flow of a liquid in a pipe or stream of any sort. In the case of the liquid we find that the lines of equal level, which lines might also be called contour lines, everywhere intersect the lines of flow at right-angles. Similarly, the lines of equal temperature always intersect the lines of flow of heat at right-angles, and the electric equipotential lines are always at right-angles to the lines of flow of electricity, and by analogy to the magnetic lines of force in a similar magnetic field.

It is a comparatively simple matter to determine the position of the lines of force in a magnetic field and it is also a comparatively simple matter to determine the positions of the equipotential lines in an electrically conducting solution. If the conditions are suitably chosen it is possible to produce a magnetic field in which a map of the lines of force is almost identical with a map of the lines of flow of electricity in a solution. When this is done the system of equipotential lines of the electric field should be almost at right-angles at every point to the magnetic lines of force. It is not possible to have the two sets of lines at right-angles at every point since the magnetic field is unlimited in extent.

Work to be Done. A. A bar magnet about six or eight inches long is imbedded in a board so that its upper surface is flush with the surface of the board. The best results are obtained by using a magnetized steel rod of cylindrical cross-section and hemispherical ends. Place a sheet of rectangular cross-section paper, ruled in half-inches, on top of the board so that the center of the magnet is at the center of the paper, the magnet being lengthwise of the paper.

Sift iron filings over the paper, tapping it gently, so that the filings may arrange themselves in chains. Place a small compass needle at various points in the field and notice whether it sets itself parallel to the chains of iron filings. If so, they will represent lines of force. The points near the two ends of the magnet from

which the lines of force seem to emanate are called the poles of the magnet. With a pencil trace about a dozen lines of force from one pole of the magnet to the other and place arrowheads on them indicating the direction in which the north pole of the small compass needle points. The pole of the magnet where they begin is the north pole and the one where they end is the south pole. Locate the center of each pole as accurately as possible and note the positions of the poles on the cross-section paper.

B. A field tray with a glass bottom to which is pasted a sheet of coordinate paper, ruled in half inches, is filled to a depth of three or four millimeters with a solution of any convenient salt. Two points corresponding to the positions of the two poles found in part A are to be maintained at different electrical potentials by connecting the electrodes *A* and *B* which dip into the liquids at these points to the opposite terminals of a low voltage A.C.

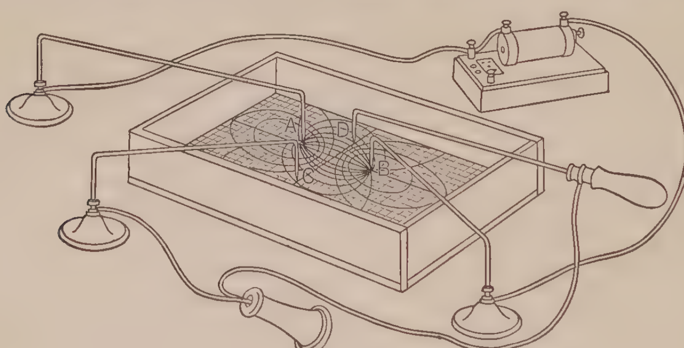


Fig. 12.—Field Tray for Locating Equipotential Lines.

source. An audio oscillator operated by a 6 or 8-volt battery is most suitable. A small induction coil is also satisfactory as a source of current. A low-voltage transformer may be used, also ordinary 110-volt A.C., provided the apparatus is in series with an incandescent lamp. *A* and *B* should coincide with the centers of the magnet poles. A third electrode *C* is placed about an inch from *A* toward *B*, and is connected through a telephone receiver to a fourth electrode *D*, which is held in the hand and used to explore the current field. (See Fig. 12.) When *C* and *D* are at the same potential, no current will flow through the telephone, which is, consequently, silent. Place *D* close to *C* and move it away from *C* until a low sound is heard in the telephone. Then move it at right angles to the direction from *C* to *D* until a region

is found in which no sound is heard. Plot the coordinates of the point in the center of this region on the paper used in part A, also plot the position of C. Using the point just found as a starting point, proceed as before. In this way, trace the equipotential line which passes through C as far as possible. Trace a complete set of equipotential lines by moving C, say, an inch at a time nearer to B and repeating the operations just outlined.

28. MECHANICAL EFFECTS OF ELECTRIC CURRENTS AND MAGNETS

Read Caswell's *An Outline of Physics*, pp. 282, 293–296.

Preliminary Exercise. Two copper wires are suspended from a frame and their lower ends dip into a mercury cup. The upper ends of the wires and the mercury cup are connected to binding posts so that current from a battery may be sent through the wires in the same or opposite directions. Connect the battery through a suitable resistance, to the two upper binding posts so that the current flows in the wires in opposite directions, and note the effect produced. Then connect the two upper binding posts to the same terminal of the battery and the mercury cup to the other so that the current flows in the same direction in both wires, and note the effect.

A spiral of wire hangs from a support and the lower end dips into a mercury cup. Connect the wire through a suitable resistance to the battery and note the effect. If the length of wire is properly adjusted the lower end of the spiral may be drawn out of the mercury, thus breaking the circuit and allowing the spiral to expand to its former length and reestablish the circuit. Thus the wire may be caused to oscillate.

The Principle of the Experiment. According to Ampere's law, whenever electric currents in parallel wires have the same direction there is a force of attraction between the wires, but whenever they have opposite directions there is a force of repulsion between them. In either case the force is inversely proportional to the distance between the wires. When the wires are not parallel the current in one of the wires may be regarded as separated into two components, one parallel to the second current and the other perpendicular to it. The law then applies only to the parallel component and not to the other. This component is the product of the current into the cosine of the angle between the two wires. Expressed mathematically, the force F (in dynes) acting on L cm. of a wire carrying a current I and forming an angle θ with a second wire carrying a current I', the distance between the section of the first wire and the second wire being d cm., is given by

$$F = \frac{II'L \cos \theta}{50\,d}, \tag{1}$$

the factor 50 in the denominator being required because of the way in which the ampere is defined.

When this law is applied to the case of two coils of wire which are near to each other, one of which is fixed in position and the other is free to turn around, it is found that the free coil tends to turn around so that its plane is parallel to that of the fixed coil and the currents circulate around the two coils in the same direction.

Apparently the atoms, or molecules, of a ferromagnetic substance such as iron behave like coils of current-carrying wire, and tend to orient themselves in the same directions in the neighborhood of a current-carrying wire as a free current-carrying coil would. Hence, iron filings and bar magnets arrange themselves along certain lines, or curves, called magnetic lines of force. Thus the region surrounding a current-carrying wire is said to be a magnetic field, and one of the wires, discussed above, is said to be in the magnetic field of the other. So there is a force acting upon any current-carrying wire in a magnetic field, whether that field is produced by a current or a magnet (i.e., by the electronic currents in the atoms of the magnet). The direction in which the North pole of a magnetic compass points in a magnetic field is the direction of the field at that point, and if L cm. of wire carrying a current I make an angle θ with the direction of the magnetic field at the point where the wire is situated, the force acting on the wire, in dynes, is given by

$$F = \frac{IHL \sin \theta}{10}, \tag{2}$$

where H is a quantity characteristic of the magnetic field at the point, and is called either the magnetizing force, or the magnetic intensity. The definition of the magnetizing force depends upon the "amount of magnetism" in a magnet, which depends upon a unit known as the "unit magnet pole."

Equations (1) and (2) are two different mathematical ways of describing the same physical fact.

Work to be Done. A. Connect the single large bundle of vertical wires furnished you in series with a storage battery, or the 110-volt D.C. mains, and a suitable resistance, and regulate the current so that the product of the current in amperes and the number of wires in the bundle shall be between 80 and 100, and place a sheet of paper so that the bundle passes through the center of the sheet. Note the direction of the current in the bundle. Sprinkle iron filings on the sheet. Tap the paper gently and the

filings will arrange themselves in chains along the magnetic lines of force. Sketch a considerable number of lines of force shown by the filings. Remove the paper and place a second sheet in the same position. Procure a small magnetic compass and place it on the sheet of paper at a distance of about an inch from the bundle of wires. Place a dot at each end of the compass needle, and then move the compass along so the dot placed at the North pole is now at the South pole. Place a new dot at the North pole, and repeat this operation until you return to the starting point. Connect the dots by a smooth curve and place an arrowhead on it pointing in the direction in which you moved the compass. This curve is a line of force. Repeat until you have about six such curves. These curves, especially those close to the wire, should form a set of concentric circles.

B. Replace the single bundle of vertical wires, used in part A, by the coil, the opposite sides of which are two bundles of vertical wires close together. Place a sheet of paper so that both bundles pass through it. Map the field with iron filings, and then on a separate sheet with the compass as was done in part A. ***Hand in all four original sheets in your final report. Do not copy them onto different sheets.***

C. Connect a 110-volt carbon lamp having a very flexible filament, in series with a lamp-bank and the 110-volt D.C. mains. Turn in one lamp in the lamp-bank and bring the North pole of a bar magnet close to the lamp with the weak filament. Note the effect. Repeat with the South pole. Which direction is the current flowing in the filament? Turn in a second lamp in the lamp-bank and repeat your observations, and so on until all the lamps in the lamp-bank are turned in. What effect does the turning in of additional lamps have upon the current in the filament? Upon the force acting upon the filament? Record all your observations. Note the dimming of the lamps in the lamp-bank and the brightening of the lamp in series as additional lamps are turned in. Explain this phenomenon in detail, perhaps using numbers to illustrate your answer.

D. Connect a small coil of wire into the circuit used in parts A and B in place of the bundles of wires and repeat part C using the coil instead of the magnet. Compare the results in the two cases. Place a rod of soft iron inside of the coil and note the effect of the introduction of the iron. Account for the effects you observe. The coil of wire and the soft iron core together constitute a simple form of electromagnet. Do you observe any tendency for the iron rod to be drawn into the coil? If so, can

you account for it? Place a non-magnetic material inside the coil instead of the iron and note results. How does the force exerted upon the filament depend upon the permeability of the medium within the coil?

E. Estimate the average distance at which you held the magnet pole from the filament in part C and assuming that the strength of the pole is 40 units, calculate the magnetizing force of the field from the equation $H = m/d^2$, where m is the pole strength and d is the distance from the filament to the pole.

Also estimate as accurately as you can the length of the filament and the current flowing through it in any particular case, e.g., with one lamp turned in, and from your data and equation (2) calculate the probable value of the force acting on the filament.

29. A STUDY OF THE PERFORMANCE OF AN ELECTRIC MOTOR

Read Caswell's *An Outline of Physics*, pp. 265–267, 308–311.

The Principle of the Experiment. This experiment is similar to Experiment 20 in which a water motor is studied, and the student should read the instructions for that experiment carefully before performing this. The energy output of the electric motor is determined in exactly the same way as the energy output of the water motor. The energy input of the water motor is the product of the pressure and the volume of water passing through the motor. The energy input of an electric motor operating on direct-current is the product of the potential difference at its terminals and the quantity of electricity passing through it. In symbols,

$$W = EQ, \qquad \text{or} \qquad W = EIt \tag{1}$$

where W is measured in joules, E in volts, Q in coulombs, I in amperes and t in seconds. Since the power input $P = W/t$,

$$P = EI. \tag{2}$$

P is expressed in watts.

These equations apply only to a motor operating on direct-current. When alternating-current is used, the maximum values of current and voltage usually do not occur simultaneously and the right hand side of these equations must be multiplied by the cosine of the "phase angle." For a discussion of this subject one should read a treatise on alternating-current machinery.

Work to be Done. A. The motor is connected in series with an ammeter, a double-pole, single-throw switch and the 110-volt D.C. mains. A voltmeter is connected by another pair of wires to the terminals of the motor. Make a tap contact to see that both instruments read in the right direction. Adjust the brake strap and spring balances as in Experiment 20.

Hold the pulley, close the switch for a moment and read both ammeter and voltmeter. Record these readings in a suitable table showing the number of revolutions per second and the data for computing both the power input, the power output, and the efficiency of the motor. Compare this table with the table for Experiment 20.

Obtain ammeter and voltmeter readings with the motor running idle. Since in both of these cases the power output is zero, the efficiency is also zero.

Make four additional sets of observations with the tension in the brake strap adjusted so that the current values are approximately equally spaced between those obtained above.

Calculate the power input and power output for each set of readings, also the efficiency, and record your results in the table mentioned above.

B. Plot a curve with efficiencies as ordinates and currents as abscissæ. Indicate on this plot the current corresponding to maximum efficiency if it can be determined from the curve. Plot a second curve using efficiencies as ordinates and speeds as abscissæ, and indicate the speed corresponding to maximum efficiency if it can be determined from the curve.

30. INDUCED ELECTROMOTIVE FORCE—THE IDEAL DYNAMO

Read Caswell's *An Outline of Physics,* pp. 300–321.

The Principle of the Experiment. The region surrounding a magnet or a current-carrying wire is a magnetic field. Whenever a wire is moved in a magnetic field in such a way that it intersects, or "cuts" magnetic lines of force, i.e., magnetic flux, there is produced (or "induced") in the wire an EMF (called an "induced EMF") which produces, or tends to produce, a current (called an "induced current") opposite in direction to that which would produce the same motion of the wire in the same magnetic field. In other words, the induced EMF tends to oppose the motion which produces it. Expressed as an equation

$$E = -\frac{\phi}{t \times 10^8}, \tag{1}$$

where E = induced EMF in volts, and ϕ = flux in maxwells cut in t seconds.

Work to be Done. A. Determine the direction of deflection of a galvanometer for a particular direction of the current flowing through it as follows: Connect one terminal of the galvanometer to one terminal of a dry cell. Then touch the thumb of one hand to the other terminal of the galvanometer and the index finger of the same hand to the remaining terminal of the dry cell. *Do not connect the cell directly across the terminals of the galvanometer.* Make sure that the coil of the galvanometer swings freely. The current passes through the galvanometer from the central carbon post of the dry cell to the marginal zinc post.

Note the direction of the winding of one of the coils of wire furnished for the experiment. Connect the coil to the galvanometer terminals. Thrust the North pole of a bar magnet through the coil. Note the direction and amount of the galvanometer deflection. What relation do you see between the direction of the lines of force from the coil and those from the magnet. Hold the magnet in the coil and note the effect. Draw the magnet out suddenly and note the effect. Go through the same procedure with the South pole. Repeat by holding the magnet still and moving the coil. Draw your conclusions. Does the induced

current tend to help or hinder the motion? Move the magnetic pole slowly through the coil. Account for the difference in deflection.

B. Connect another coil with a source of current, having a key in the circuit. Bring the face of this coil near the face of the coil connected to the galvanometer. If possible, one of the coils may be slipped inside the other. Press the connecting key and note the action of the galvanometer. Hold the key down for a few seconds and note the result. Release the key, and again note the result. Place a soft iron rod through both of the coils and repeat. Connect the ends of this core with soft iron and repeat, noting the effects. How do you account for the effects produced by the iron?

C. An "ideal dynamo" is so constructed that a ratchet may be lifted, allowing a spring to rotate a flat coil of wire through ten degrees about an axis perpendicular to the direction of the magnetic field. If the spring is kept wound up to the same tension at all times, the speed of rotation of the coil will be uniform. The terminals of the coil are connected to two separately insulated copper rings attached to the shaft. By means of brushes these rings are connected to the binding-posts of the dynamo and thence to the galvanometer.

Connect the dynamo to the galvanometer and allow the armature to rotate through ten degrees. From the direction of deflection of the galvanometer determine the terminal where the current leaves the armature, and by inspection of the dynamo determine the relation between the direction of the current in an individual section of the armature winding, its motion in the magnetic field and the direction of the field. It will be convenient to determine the direction of the field by means of a small magnetic compass.

State the relation which you have just found to exist between these three directions. If the resistance of the circuit is constant and also the speed of rotation of the armature, the EMF induced will be proportional to the galvanometer deflection. Why? Note the galvanometer deflections for ten degree intervals during a trifle more than one complete revolution of the armature. Using rectangular cross-section paper plot galvanometer deflections as ordinates and angular displacements of the armature as abscissæ. Does your graph show any resemblance to a sine curve? If so, why? How can this dynamo be modified so as to produce direct instead of alternating current? What would be the effect of putting an iron core inside the windings of the armature?

31. CONDENSERS AND CAPACITY

Read Caswell's *An Outline of Physics*, pp. 325–333.

The Principle of the Experiment. The capacity of a condenser is the quantity of electricity which is required to produce a difference of potential between its plates of one volt. The method of determining the capacity employed in this experiment is that of comparing the amount of electricity required to charge the unknown condenser to a certain potential with that required to charge a condenser of known capacity to the same potential. If a charge of electricity is sent through a galvanometer whose period of vibration is comparatively long, the deflection of the galvanometer is proportional to the quantity of electricity passing through it. Such a galvanometer is called a ballistic galvanometer.

If a ballistic galvanometer G, a condenser C, a battery B and a single-pole, double-throw switch, or condenser key, K, be connected as shown in the Fig. 13, when the switch K is closed so as to connect the condenser and the battery through it, the condenser will be charged to the potential of the battery. If C is the value of the capacity in farads and E the potential in volts, the charge Q expressed in coulombs will be given by the equation

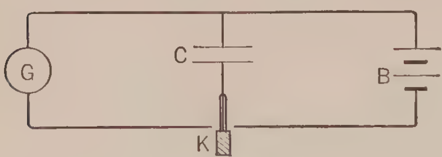


Fig. 13.

$$Q = CE. \tag{1}$$

If the switch is then reversed so as to connect the condenser and the galvanometer through it, the condenser will be discharged, the charge Q passing through the galvanometer and producing a deflection d. Since the observed deflection of the galvanometer is proportional to Q, we may write

$$Q = kd,$$

where k is a constant, depending upon the galvanometer, arrange-

ment of the scale, etc. It follows that

$$CE = kd, \qquad \text{or} \qquad C = \frac{k}{E}d, \tag{2}$$

whence

$$C = jd, \tag{3}$$

where j is a constant as long as E is constant.

Work to be Done. A. Connect the standard condenser which is furnished you to the source of potential, which is assigned by the instructor, and to the galvanometer in accordance with the above figure. Charge the condenser by closing the key K so as to connect to the battery to the condenser, and then as quickly as possible reverse the key so as to discharge the condenser through the galvanometer, and note the deflection of the galvanometer. ***Be careful to keep fingers on insulation and off metal.*** Repeat this operation a number of times until you have a consistent set of observations. From the mean of these deflections and the known value of C calculate j.

Replace the standard condenser by a condenser of unknown capacity and repeat your observations. From the mean of this set of deflections and the value of j just determined calculate the capacity of the condenser.

B. Repeat with a second condenser of unknown capacity.

C. Connect the two "unknown" condensers in series and determine their combined capacity. Also compute their combined capacity by means of the equation

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2}.$$

How closely does the computed result agree with the observed?

D. Connect the two condensers in parallel and determine their combined capacity, and compute their combined capacity from the equation

$$C = C_1 + C_2.$$

How closely do the observed and computed results agree in this case? How would you connect condensers if you wished to obtain a capacity greater than that of any one of them? Less than that of any one of them?

32. CHARACTERISTICS OF A THREE-ELECTRODE VACUUM TUBE

Read Caswell's *An Outline of Physics*, pp. 336–345.

The Principle of the Experiment. A three-electrode vacuum tube contains a filament which is heated by a battery known as the "A" battery, a "grid" made of wire gauze, or similar material, and a sheet of metal, known as the "plate." The plate is connected through a battery known as the "B" battery to one terminal of the filament. The grid is between the filament and the plate. No current will flow through the plate circuit unless a supply of electrons is available in the tube. When the plate is connected to the positive terminal of the "B" battery and the filament to the negative terminal, a current will flow through the plate circuit provided the filament is heated so that it emits electrons. The magnitude of the "plate current" depends upon the supply of electrons furnished by the filament, and this depends upon the "filament current." The curve showing the relation between the plate current and the filament current is one of the "characteristics" of the tube.

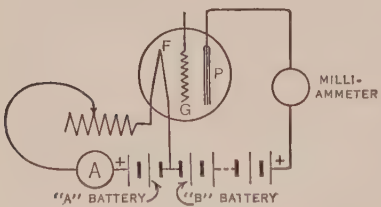


Fig. 14.

If the grid is connected to a source of potential and its potential varied in some manner, it may either facilitate the passage of electrons from the filament to the plate, or it may retard this flow. The plate current, therefore, depends upon the potential, or voltage, of the grid. The curve showing the relation between the plate current and the grid voltage is a second "characteristic" of a three-electrode tube. Such a tube is often called an "audion," and the curve is called the "audion characteristic."

Work to be Done. A. Connect an audion as shown in Fig. 14. Any ordinary commercial tube will serve the purpose. For the "A" battery use one or two dry cells, if the maximum current as indicated on the tube or the box in which it is shipped is less than half an ampere. Be sure that no more current is sent through the

filament than it is intended to take. If the filament is intended to take in the neighborhood of an ampere, a six-volt storage battery may be used. For the "B" battery use a 22-volt dry battery. For the ammeter in the filament circuit an ordinary D.C. ammeter reading to 1.0 amperes may be used. Instead of a milliammeter to measure the current in the plate circuit, a voltmeter may be used. The Weston Model 280 voltmeter takes a current of 15 milliamperes for full scale reading.

By increasing the resistance in the filament circuit vary the filament current from the maximum permissible down to nearly zero, by small steps, and record the corresponding values of the plate current and filament current.

On rectangular cross-section paper plot the values of the plate current as ordinates and those of the filament current as abscissæ, and draw the plate current-filament current curve.

B. Reverse the connections of the "B" battery and repeat part A.

C. Repeat part A, using a 45-volt battery instead of the 22-volt battery previously used.

D. Connect the tube used in part A as shown in Fig. 15,

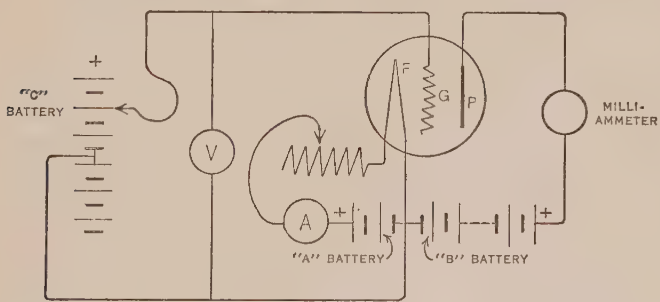


FIG. 15.

using the same "A" and "B" batteries as in part A. Also use the same ammeter in the plate circuit. The resistance previously used in the filament circuit should be left in the circuit. For the "C" battery use a 45-volt dry battery. Connect the mid-point of the "C" battery to the negative terminals of the "A" and "B" batteries. Keeping the filament current and plate voltage constant, vary the grid voltage from zero to positive values by moving the movable connection on the "C" battery two or three cells at a time toward the positive end of the battery. If the plate current suddenly becomes very much larger than pre-

viously, discontinue your observations. Then change the potential of the grid from zero to negative values by moving the movable connection two or three cells at a time toward the negative end of the battery, reversing the connections to the voltmeter before you do this. Record all the values of the grid voltage, including zero, and the corresponding values of the plate current. Plot the plate currents as ordinates and the grid voltages as abscissæ, and draw the audion characteristic.

E. Repeat part D, using a smaller value of the filament current.

F. Repeat part D, using a "B" battery of, say, 67 or 90 volts.

33A. ELECTROLYSIS OF COPPER

Read Caswell's *An Outline of Physics*, pp. 357–365.

Preliminary Exercise. One glass jar is filled with a copper sulphate solution and another one with a solution of some salt.

(1) Place a strip of copper (the anode) and a nickel or a piece of iron (the cathode) to be plated in the copper sulphate solution. Connect the anode and cathode to a source of direct current such as a storage battery so that the current will pass from the anode to the cathode. After about five minutes examine the copper anode and the cathode. What is the effect on each?

(2) Wash off the electrodes and place them in the second tumbler containing the salt solution. Repeat (1) and note the effects.

The Principle of the Experiment. According to Faraday's law of electrolysis, whenever an electric current passes across the junction between a purely metallic conductor and a purely electrolytic conductor a chemical change or chemical changes occur the amount of which, expressed in chemical equivalents, is exactly proportional to the quantity of electricity which passes and is independent of everything else. Hence, if a current is sent through an electrolytic cell containing a metal anode and a metal cathode, metal will go into solution at the anode, and under favorable conditions the metal dissolved off the anode will be plated on to the cathode. If m = mass of metal transported through the solution by the current I in the time t,

$$m = kIt, \tag{1}$$

where k = electrochemical equivalent of the metallic ion transported. The chemical equivalent of the metal is its atomic weight divided by its valence. Let this ratio be denoted by Z, then

$$k = \frac{Z}{96{,}500}, \tag{2}$$

when k is measured in coulombs per gram.

The coulombmeter consists of a glass jar which should be filled with a solution of copper sulphate having a density of about 1.16 and one per cent of free sulphuric acid, a sheet of copper to be

used as an anode, and a second sheet of copper to be used as a cathode. When a current is sent through the coulombmeter it should not exceed one ampere for every 80 square centimeters of the area of the cathode. To prepare the cathode for use: Wash the hands with soap and rinse thoroughly. Polish the cathode carefully with sand paper, wash in cold water, rub with a clean cloth free from oil, dry under gentle heat, cool and weigh on a sensitive balance. In cleaning the cathode it should be laid on a fresh piece of clean paper.

Work to be Done. A. Having first cleaned the cathode and weighed it as directed above, connect the coulombmeter *in series* with an ammeter, a lamp rheostat, and a double-pole single-throw switch which is connected to the 110-volt D.C. circuit. Adjust the resistance in the rheostat so as to give the proper amount of current. Close the switch noting the time to the nearest second. Read the ammeter at intervals of one minute for an hour. Open the switch, again noting the time. Lift the cathode out of the solution and place it in a vessel containing very dilute sulphuric acid, rinse thoroughly with distilled water, dry with filter paper and then warm slightly to drive off any remaining moisture, cool and weigh.

From the average current, I, in amperes, the total time, t, in seconds and the gain in weight, M, in grams, calculate the electrochemical equivalent of copper from equation (1).

B. If the electrochemical equivalents are proportional to the quotients of the atomic weights and valencies, from equation (2) calculate the electrochemical equivalent of hydrogen, given: atomic weight of $H = 1.0077$, valence of $H = 1$, atomic weight of Cu (cupric) $= 63.6$, valence $= 2$. Express your results in (1) grams per coulomb, and (2) coulombs per gram. The latter method of expression is frequently used by chemists.

In a similar manner calculate the electrochemical equivalents of a number of typical elements, using atomic weights and valencies as given in standard tables.

C. What is the sign of the charge carried by a copper ion in electrolysis? By a hydrogen ion? By a sulphate ion? By metal ions? By halogen ions?

33B. ELECTROLYTIC DECOMPOSITION OF WATER

Read Caswell's *An Outline of Physics*, pp. 357–365.

The Principle of the Experiment. Pure water is a very poor conductor of electricity, but if a small amount of some salt is dissolved in the water, the solution is conducting; and when a current flows through it the water molecules are decomposed into hydrogen and oxygen. The oxygen molecules collect at the place where the current enters the solution (called the *anode*) and the hydrogen ions collect at the place where the current leaves it (called the *cathode*).

Fig. 16 shows Hoffman's apparatus for the electrolytic decomposition of water. The two stop-cocks are opened and a dilute solution of sodium sulphate (Na_2SO_4), or some similar salt, is poured into the thistle tube until it begins to run out through the stop-cocks. The stop-cocks are then closed. At the bottom of each of the graduated tubes is a sheet of platinum connected by a fine wire to a binding-post in the base. If the binding-posts are connected into a suitable electric circuit, oxygen will begin to accumulate at the anode and hydrogen at the cathode. When the gas bubbles are large enough they will break away from the electrodes and rise to the tops of their respective graduated tubes. The pressure of the gas collected in a graduate tube is due to the atmospheric pressure exerted upon the surface of the water in the thistle tube plus the pressure of the column of water between the level in the graduated tube and the thistle tube. This may be computed as in Experiment 9.

FIG. 16.—Hoffman's Apparatus for the Electrolysis of Water. (Courtesy of the Central Scientific Company.)

From Avogadro's law a mole, or gram-molecule, of the gas occupies 22.412 liters under a pressure of one standard atmosphere at 0° C. By determining the temperature of the gas (it will be at room temperature if allowed to stand for a short time), its pressure and its volume, the mass of the gas may be determined from a knowledge of its molecular weight. For oxygen the molecular weight is, by definition, 32, and for hydrogen 2.016. The mass may also be calculated from the equation $pv = NRT$. If p is

expressed in atmospheres, and v in liters, and if T is the absolute temperature in Centigrade degrees, $R = 0.082$ and N is the number of moles of the gas. The mass $m = NM$, where M = molecular weight.

Faraday's law of electrolysis states that whenever an electric current passes across the junction between a purely metallic conductor and a purely electrolytic conductor a chemical change or chemical changes occur the amount of which, expressed in chemical equivalents, is exactly proportional to the quantity of electricity which passes and is independent of everything else. Expressed mathematically,

$$m = kIt, \qquad \text{or} \qquad m = kQ \tag{1}$$

where k = the electrochemical equivalent in grams per coulomb and I is the current in amperes which flows through the solution for a time t seconds. Q is in coulombs.

Work to be done. A. Fill the apparatus with a salt solution as directed above, and then connect the apparatus in series with a storage battery, an ammeter, a suitable resistance and a switch. Close the switch and quickly adjust the resistance so as to give a current of about half an ampere. Open the switch. Then open the stop-cocks for an instant to allow any gas which may have collected in the tubes to escape. Close the switch again, noting the instant at which it was closed. Observe the ammeter readings at intervals of one minute until the tube which has the most gas in it is nearly full of gas. Stop the current, noting the instant at which it was stopped. From the average value of the current and the elapsed time compute the number of coulombs which have passed through the solution. After a few minutes record the volume of each of the gases as shown by the apparatus, also the room temperature. Calculate the pressure separately for each of the gases.

Compare the volumes of the two gases liberated if subjected to the same pressure. What does this tell you about the relative number of molecules of hydrogen and oxygen?

B. From the pressure, volume and temperature calculate the mass of each of the gases liberated and from these values calculate the electrochemical equivalents of both oxygen and hydrogen.

34. RESISTIVITY OF AN ELECTROLYTE

Read Caswell's *An Outline of Physics*, pp. 357–367 and Experiment 23 in this manual.

The Principle of the Experiment. The measurement of the resistivity of an electrolyte is a more complicated problem than that of a metallic conductor owing to the phenomenon of polarization which occurs at the electrodes of the electrolytic cell. The effect of polarization may be overcome in a number of ways, one method involves the use of a source of alternating current to operate a Wheatstone bridge. A telephone is then used instead of a galvanometer and the resistances of the bridge are adjusted to quench any noise in the telephone. Unless the circuit is absolutely free from any capacity or inductance it is difficult to secure a balance of the bridge.

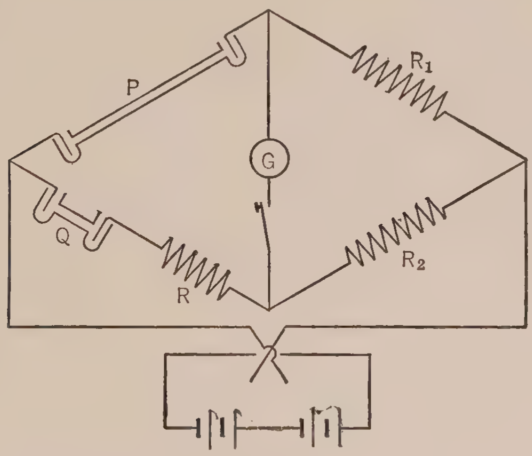


Fig. 17.

In the method employed in this experiment a Wheatstone bridge is used and it is operated by a direct current battery with a galvanometer in the usual way. One "arm" of the bridge, shown in Fig. 17, contains an electrolytic cell P, a second "arm" contains another electrolytic cell Q and a resistance R, the third and fourth arms contain the resistances R_1 and R_2, which are equal. The resistance R, which is in series with the cell Q, is adjusted

until no current flows through the galvanometer. When this condition is achieved,

$$R_p = R_q + R, \tag{1}$$

where R_p = resistance of cell P, and R_q = resistance of cell Q.

The cell P consists of two test tubes joined by a piece of capillary tubing about 30 cm. long. See Fig. 18. Similar electrodes of platinum foil are placed in the test tubes opposite the ends of the capillary tube. The electrolyte whose resistivity is to be determined, is poured into the cell until the electrodes are covered. The cell Q is exactly the same as the cell P except that the capillary tube is only 3 or 4 cm. long. It is important that the two cells be made as nearly alike as possible except in this one respect, and that they should be filled to exactly the same depth.

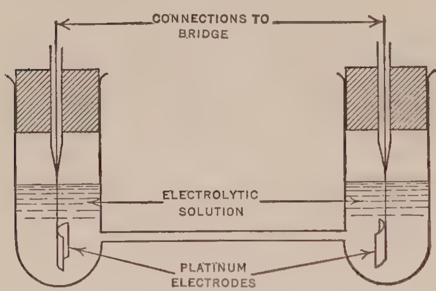


FIG. 18.

Then the difference in the resistance of the two cells is simply the resistance of the electrolyte contained in the extra length of the capillary in cell P. If the length of the capillary in cell P is L_p and that in cell Q is L_q, and if A = cross-sectional area of the capillary, which must be as nearly uniform as possible throughout,

$$R = \frac{\rho(L_p - L_q)}{A}, \text{ or } \qquad \rho = \frac{AR}{(L_p - L_q)}, \tag{2}$$

where ρ = resistivity of the electrolyte.

In equation (2) all the factors are constant except ρ and R, which are proportional to each other. If R is measured for an electrolytic solution whose resistivity is known, the resistivity of any other electrolyte can be found directly from its value of R. This procedure eliminates the necessity of determining the area of the capillary tubes and their lengths.

Work to be Done. A. Connect up a Wheatstone bridge circuit as shown in Fig. 17, using 1000 ohm resistances for R_1 and R_2. Use a galvanometer of high resistance or else connect a high resistance in series with it. Use a battery of from 10 to 30 volts. For R use a resistance adjustable in small units, down to, say,

0.1 ohm. Connect the battery to the bridge circuit through a double-pole, double-throw, reversing switch.

Prepare a solution of known concentration of some salt, the resistivity of the solution being obtained from standard tables.

Fill the cells P and Q to the same depth with the solution, perhaps using a medicine dropper to fill them, so as to make the adjustment as accurate as possible.

Having connected the cells into the bridge circuit, adjust R until no current flows through the galvanometer when the galvanometer key is closed. Record the value of R.

Empty the solution out of P and Q then rinse thoroughly, and refill them to exactly the same depth with the electrolyte whose resistivity is to be determined. Determine R, and calculate ρ for the electrolyte.

B. Repeat part A, determining the resistivity of a second electrolyte.

C. Make an absolute determination of the resistivity of one of the solutions used by determining L_p, L_q, and the cross-sectional area A. To measure the cross-sectional area of the capillary a thread of mercury 2 or 3 cm. long may be run into the tube and its length measured in several positions. If the cross-section is uniform, the length will be constant. Run the mercury out into a watch glass and weigh it on a chemical balance. From its density determine the volume of the mercury, and from its volume and the length of the mercury thread determine A.

Calculate the resistivity, using equation (2). How does this value of the resistivity compare with the value previously found for the same solution?

35. VOLTAIC CELLS

Read Caswell's *An Outline of Physics*, pp. 363–369.

The Principle of the Experiment. If two plates are put into a chemical solution and if the characteristic electrode potentials between the plates and the solution are not the same, the plates will be at different electric potentials, and a current will flow from one to the other if they are connected. This combination is known as a primary voltaic cell. The cell therefore has an EMF, the value of which depends upon the nature of the plates and the solution. The EMF is characteristic of the cell, but the current which it will send through a circuit of course depends upon the resistance of the circuit and any counter EMF's which may exist in it. In secondary voltaic cells, i.e., storage cells, the plates are the same when the cell is "uncharged," but in the process of charging they become covered with different materials and so they become to all intents and purposes for the time being primary voltaic cells.

Work to be Done. A. Fill a glass jar about two-thirds full of a solution of ammonium chloride (NH_4Cl) and introduce into the solution two strips, one of zinc, the other of another metal or of carbon. For convenience, these strips may be held in clamps furnished with the apparatus. With a copper wire connect each strip or its clamp to one terminal of a low-voltage voltmeter. Notice the motion of the pointer, or needle, of the instrument. Does interchanging the connections affect the direction of the motion? If the zero of the instrument is at one end of the scale, which of the elements of the cell should be attached to the binding post marked +? This one is called the positive pole of the cell. Do different substances used as the positive pole, e.g., carbon, copper, nickel, all give the same voltage? List the materials used for the positive pole in the order of the voltage they give with zinc as the other element.

B. Set up a cell with fresh electrodes of zinc and either copper or carbon, or with both elements freshly scrubbed and heated too hot to touch (avoid melting any of the metals). Connect as before to the instrument and observe the deflection of the pointer for a minute. Is this deflection steady? Short circuit the cell half a minute by holding a strip of copper in contact with the two elements or their clamps. Is the voltage the same after removing

the short circuit as before it was applied? The phenomenon observed is called polarization.

C. Set up the cell again, having the zinc in the ammonium chloride solution, but putting the strip of copper in a porous cup containing copper sulphate ($CuSO_4$) solution and a few crystals of copper sulphate, the cup being also set down into the liquid in the jar. Test this cell as before for polarization. How does it compare with the one-fluid cell? After it has been giving current for some time, take out the copper strip and examine its surface. Is it changed in any way? Has this any relation to the greater or less degree of polarization?

When through put back all solutions into their stock bottles, rinse the jar, cup and electrodes, and leave them so they can drain satisfactorily.

D. Fill a glass jar about two-thirds full of a strong solution of sulphuric acid and in the solution place two corrugated lead plates or grids having the grooves filled with spongy lead. Connect the grids to the terminals of the voltmeter. Does the voltmeter indicate any voltage? Is it supplying any current?

Disconnect the voltmeter and connect the plates in series with a rheostat, an ammeter reading to, say, 10 amperes, and a source of direct current. A six-volt storage battery will do. Be very careful to have enough resistance in the circuit to prevent the current from being too large for the ammeter. Regulate the resistance until you have a current of, say, 5 amperes. Allow the current to flow for about half an hour, disconnect the battery and again measure the voltage of the cell. From which of the grids does the current flow? Which of the grids is at the higher potential? How do you know? You now have a lead storage cell partially charged. Short circuit the cell by connecting the grids with a heavy piece of wire and leave it so connected.

36A. ILLUMINATION, CANDLE-POWER, AND INTRINSIC BRIGHTNESS

Read Caswell's *An Outline of Physics*, pp. 377–380.

The Principle of the Experiment. The amount of light received by a surface from a luminous source of light depends upon the amount of light energy emitted by the source in a unit of time and its distance from the surface. Expressed mathematically

$$\mathcal{I} = I/d^2, \tag{1}$$

where $\mathcal{I}$ is the illumination produced upon a surface at a distance d from a source of light whose candle-power is I.

The effect upon the eye when looking at a source of light not only depends upon these factors but it also depends upon the "intrinsic brightness," or brilliancy, of the source.

Work to be Done. A. A right-angled prism of wood is provided. This is painted white and is to be used as a luminometer (a type of photometer) by placing it on the table with the edge between the mutually perpendicular faces uppermost. Place the luminometer at a distance of several feet from a window, so that its upper edge is perpendicular to a line joining it to the window. Note that the side next the window is much brighter than the other. Explain. Place a large piece of white cardboard a foot or so away from the luminometer on the side opposite the window and see whether it is possible to increase the illumination on that side. Explain the result.

B. Replace the cardboard by an incandescent lamp, and remove the lamp farther and farther away from the luminometer. What effect does the increase in distance have upon the illumination? Can you remove the lamp to such a distance that the illumination due to it is less than that due to the window? If so, why is it that you cannot look directly at the lamp? What is meant by "intrinsic brilliancy," or brightness?

C. See whether, on the basis of the observations of parts A and B, you can name three factors upon which the illumination of a surface depends. Two of these are frequently combined into one, which is known as "candle-power," and is a measure of the amount of light energy (expressed in convenient units) emitted by a source of light per second.

D. Shielding the luminometer from light coming from the windows, place two lamps of known candle-power on opposite sides of it, and adjust their distances from it until the illuminations produced are the same (the two faces of the luminometer will appear equally bright). From your results show (1) that the candle-powers of two sources of light producing equal illuminations on a surface are proportional to the squares of the distances of the sources from the surface, and (2) that the illumination produced by a single source of light upon any surface is, therefore, inversely proportional to the square of the distance from the surface.

E. Again setting the luminometer as in part A balance the illumination produced by the window with that of a lamp of known candle-power. Measure the distance from the luminometer to the lamp and also to the window, and calculate the equivalent candle-power of the window.

F. The illumination in foot-candles is equal to the candle-power of the source divided by the square of the distance to the surface in feet. Calculate the illumination of the surface in part E.

36B. MEASUREMENT OF CANDLE-POWER BY A PHOTOMETER

Read Caswell's *An Outline of Physics*, pp. 377–382.

The Principle of the Experiment. It is impossible to compare the intensities of two light sources directly. Therefore all photometric measurements depend upon producing equal illuminations upon a suitable surface by two lamps, the distances of the two lamps from the surface and the candle-power of one of them being known. When this adjustment has been made

$$I_1/I_2 = d_1^2/d_2^2, \tag{1}$$

where I_1 and I_2 are the intensities of the two sources of light, and d_1 and d_2 are the corresponding distances from the illuminated surface.

Candle-power is a measure of the rate of emission of energy in the form to which the eye is sensitive and which we call "*light.*" The efficiency of a light source is the ratio of the candle-power of the source to the power input of the lamp. The efficiency is usually expressed either in candle-power per watt, or in lumens per watt. 1 candle-power = 4π lumens.

To obtain the true, or what we may call the absolute, efficiency we should express the power output in the same units as the power input, i.e., in watts. 668 lumens = 1 watt.

The "standard" lamp, whose candle-power is known, is placed at one end of an optical bench and the lamp to be tested is placed at the other. A movable photometer screen is moved to and fro along the optical bench until a place is found where the illumination produced by the one lamp cannot be distinguished from that produced by the other. The screen is arranged so that part of it is illuminated by one lamp and another part illuminated by the second lamp, the two parts being side by side. When the observer cannot distinguish between the two parts the adjustment is correct.

By examining the particular photometer with which he is working the student will very soon discover the specific way in which his instrument provides for the comparison. For brief descriptions of a few typical photometers the student may read pages 380 and 381 of the author's text-book, "*An Outline of Physics.*"

Work to be Done. A. Place a lamp whose candle-power at a certain voltage is known in the holder on one end of the optical bench and the lamp to be tested in the holder at the other end. Connect each in series with separate rheostats and ammeters. Connect voltmeters to the terminals of the lamps. Adjust the resistance in series with the standard lamp until the voltage at its terminals is that at which it was standardized. Record its candle-power and corresponding voltage. Slide the photometer screen along the bench until the illumination is the same for both lamps. Measure the distances from both lamps to the screen and calculate the candle-power of the test lamp from the known candle-power of the standard. Record the ammeter and voltmeter readings for both lamps and calculate the power consumed by each. From the preceding results calculate the efficiency of each lamp in candle-power per watt.

B. Vary the resistance in series with the test lamp so that the voltage at its terminals changes by intervals of about ten volts from a voltage slightly higher than its rated voltage down to one where the filament is scarcely luminous. In this way obtain a series of values of its candle-power and efficiency for various voltages.

Using rectangular cross-section paper plot curves showing the relations (1) between candle-power and voltage, and (2) between efficiency and voltage. The same sheet of paper may be used for both curves, with voltages as abscissæ and candle-powers and efficiencies as ordinates. Place the scale for candle-power at the left and that for efficiency at the right, or vice versa.

C. Replace the test lamp previously used by one of a different material and compare their efficiencies at different voltages. Which is the more efficient, a carbon lamp or a tungsten lamp?

D. Calculate the true efficiency of the standard lamp when burning at its rated voltage.

36C. MEASUREMENT OF CANDLE-POWER BY THE LUMINOMETER

Read Caswell's *An Outline of Physics*, pp. 377–383.

The Principle of the Experiment. With the ordinary photometer it is impossible to compare satisfactorily the intensities of lights of different colors. The luminometer is based on the fact that light is used for seeing things by, that is, distinguishing objects and differences between objects. Thus any two lights, regardless of their colors, have the same intensities if, at the same distance from them, objects can be seen with the same distinctness. The luminometer is a black box to screen off extraneous light and allow only the light from the source which is to be observed to fall on a chart consisting of a jumble of black letters on white paper, or some similar object. Could colored letters or paper be used? Why is a jumble of letters used instead of a page of ordinary reading matter? Note that the eye should always be at the same distance from the chart. The illumination produced by a lamp is proportional to the square of the distance between the lamp and the illuminated surface. If two light sources are placed, successively, at distances such that they give equal illumination on the luminometer surface,

$$I_1/I_2 = (d_1/d_2)^2, \tag{1}$$

where I_1 and I_2 are the intensities of the two sources of light, and d_1 and d_2 are the corresponding distances from the illuminated surface.

Candle-power is a measure of the rate of emission of energy in the form to which the eye is sensitive and which we call "*light.*" The efficiency of a light source is the ratio of the candle-power of the source to the power input of the lamp. The efficiency is usually expressed either in candle-power per watt, or in lumens per watt. 1 candle-power = 4π lumens.

To obtain the true, or what we may call the absolute, efficiency, we should express the power output in the same units as the power input, i.e., in watts. 668 lumens = 1 watt.

Work to be Done. A. Connect a lamp socket in series with a rheostat and an ammeter, and connect a voltmeter across its terminals. Insert in the lamp socket a standard lamp (approximately white light) whose candle-power at a given voltage is known.

Record these data. Adjust the resistance in the rheostat until the lamp is burning at its rated voltage. While one experimenter moves the lamp along the axis of the light tube, let the other determine the distance at which he is barely able to distinguish capital letters but is unable to distinguish small letters. Both experimenters should make this determination, which may vary considerably between individuals.

Record ammeter and voltmeter readings. Calculate the power consumed by the lamp, also its efficiency in candle-power per watt.

B. Replace the standard lamp by an uncolored lamp to be tested. Determine the distance it must be placed from the chart. Calculate its candle-power from the known candle-power of the standard. Record the ammeter and voltmeter readings, and calculate both the power consumed and the efficiency of the lamp. Repeat for lamps of as many colors as possible, both carbon and tungsten. Which is the more efficient, a carbon or a tungsten lamp?

C. Using one of the lamps tested in part B, vary the voltage applied to it, noting the values of both current and voltage, and determine the candle-power of the lamp at different voltages. Calculate its efficiency in candle-power per watt at different voltages. Using rectangular cross-section paper plot curves showing the relations (1) between candle-power and voltage, and (2) between efficiency and voltage. The same sheet of paper may be used for both curves, with voltages as abscissæ and candle-powers and efficiencies as ordinates. Place the scale for candle-power at the left and that for efficiency at the right, or vice versa.

D. Calculate the true efficiency of the standard lamp when burning at its rated voltage.

37. MIRRORS

Read Caswell's *An Outline of Physics*, pp. 387–392.

Preliminary Exercise. Place a plane mirror on edge on a sheet of paper so that the mirror is in a vertical position. Against the face of the mirror stick a pin into the paper so that the pin is vertical. Three or four inches from the first pin and in front of the mirror place a second pin so that the line joining the two pins forms an angle of, say, 60° with the surface of the mirror. Place a third pin in front of the mirror in such a position that it appears to be in the same straight line with the first pin and the image of the second.

Draw a line marking the position of the reflecting surface of the mirror. Remove the mirror and draw lines showing the path of the light from the second pin to the third, remembering that the light is reflected, not at the position of the first pin but at the reflecting surface beyond it. Draw a normal i.e., a perpendicular to the mirror at the point where the light is reflected from it and with a protractor measure the angles of incidence and reflection as accurately as possible.

Repeat, using a different angle of incidence, say, 45°.

The Principle of the Experiment. According to the law of reflection of light the angle that an incident ray makes with the normal (i.e., the perpendicular) to the mirror at the point of incidence is equal to the angle that the reflected ray makes with the normal, and the angles lie in the same plane. As a consequence, it appears that a line drawn through a point object and its image formed by the mirror should lie on a straight line perpendicular to the surface of the mirror.

It also appears that if the mirror is spherical, the distance of the object from the mirror, the distance of the image from the mirror, and the radius of curvature of the mirror, are connected by the following equation:

$$\frac{1}{u} + \frac{1}{v} = \frac{2}{r}, \tag{1}$$

where u = object distance, v = image distance, and r = radius of curvature. The quantity $r/2$ may be replaced by f, where f is called the focal length of the mirror. u is taken positive for a real object, negative for a virtual object; v is taken positive for a real

image, negative for a virtual image; f is positive for a concave mirror, negative for a convex mirror. In the case of a plane mirror r is infinite, so $2/r = 0$, and $v = -u$. Hence the image formed by a plane mirror is as far behind the mirror as the object is in front of it, virtual images formed by a mirror always being behind the mirror. In the case of a spherical mirror, if the object is very far away, $1/u = 0$, and $v = r/2$, or $v = f$.

If the size of an object is denoted by O, and the size of the image by I, we find that

$$I/O = v/u. \tag{2}$$

The ratio I/O is called the magnification.

Work to be Done. **A.** Set a plane mirror on edge on a sheet of paper so that the mirror is in a vertical position. At a convenient distance directly in front of it set up a large headed pin. Place a similar taller pin behind the mirror and adjust it at such a distance and in such a position that looking at it from any position in front of the mirror it seems to be a prolongation of the image of the first pin. This is known as the method of parallax. Measure the distances of the two pins from the silvered surface of the mirror. Draw a straight line from the first pin to the second and also a line along the face of the mirror and measure the angle formed by these two lines. Record your conclusions.

B. Set up a concave mirror, preferably on an optical bench, with its axis parallel to the bar of the bench, point the bench toward an open window, and adjust a small white screen until the image of a distant object is sharply focussed on the screen. Measure the distance from the mirror to the screen. What name is given to this distance? What sort of an image was obtained?

C. Set the same concave mirror used in part B near one end of the bench, and near the other end of the bench, but slightly to one side, set a screen with an opening, with a lamp just beyond for illumination. Locate the image of this screen in a manner similar to that used in part B. From the formula $1/u + 1/v = 1/f$ compute f. How does this compare with the result of part B? See if it is possible to interchange the positions of object and image. Using for the object and image screen ground glass with millimeter rulings, or as object an opening whose size can be measured, determine the magnification, and see how it compares with the distances of object and image from the mirror.

D. Adjust a pin in front of the concave mirror at such a distance and in such a position that the head of the pin and its image will exactly coincide, as shown by the parallax test.

Measure the distance from the mirror to the pin. What is this distance? How does it compare with f.

E. Place the pin in front of the concave mirror at a distance considerably less than f. Locate its image by the parallax method of part A. Compute f by equation (1) putting $r/2 = f$. A similar measurement and computation may be made with a convex mirror.

38A. INDEX OF REFRACTION BY MICROSCOPE

Read Caswell's *An Outline of Physics*, pp. 392–396.

Preliminary Exercise. Place a glass cube on top of a sheet of paper lying on the table. Against opposite faces of the cube stick two pins into the paper so that the pins are vertical. Choose the positions of the pins so that the line joining them makes angles of about 60° with the faces of the cube. Stick a third pin into the paper at a distance of three or four inches from the first, so that the third, first and second appear to lie in a straight line. Finally, stick a fourth pin into the paper at a distance of three or four inches from the second, so that the third, first, second and fourth appear to lie in one straight line.

Draw lines marking the positions of the two faces of the cube. Remove the cube and draw lines showing the apparent path of light from the third pin to the fourth. Draw normals (i.e., perpendiculars) to the glass surfaces at the positions of the first and second pins, and with a protractor measure the two angles of incidence and the two angles of refraction as carefully as possible.

Repeat the above exercise, placing the first two pins so that the line joining them makes different angles with the glass surfaces, say 70° instead of 60°.

How nearly constant is the value of the index of refraction you find from the following relation?

$$\text{Index of refraction} = n = \frac{\text{Sine of angle in air}}{\text{Sine of angle in glass}}\cdot$$

Place the first two pins almost directly opposite each other and near to two adjacent parallel edges of the cube. See whether you can with the aid of the other two pins trace a path of light in which reflection occurs at the face of the cube bounded by the two edges just mentioned. This phenomenon is called total reflection. Hint. In the first two parts of this exercise the line joining the first and third pins is parallel to that joining the second and fourth, but in this case the two lines will intersect at a point outside the cube.

The Principle of the Experiment. According to Snell's law of refraction, the index of refraction, n, of a substance is given by the equation

$$n = \sin i/\sin r, \tag{1}$$

where i is the angle of incidence in air, and r is the angle of refraction in the substance. If the light is passing *from* the substance

into the air, the words "incidence" and "refraction" may be interchanged in the preceding statement.

From this law it can be shown that if an object is at a depth d below a plane surface, it will appear to be at a depth d', and if n = index of refraction,

$$n = d/d'. \tag{2}$$

If the surface is spherical, convex upward,

$$n = \frac{d(r - d')}{d'(r - d)}, \tag{3}$$

where r is the radius of curvature of the surface.

Work to be Done. A. Place a glass cube on a table and focus the micrometer microscope on an ink spot or some chalk dust on the upper side of it. Turn it over so the mark is on the lower side, and observe the distance that the microscope carriage must be lowered in order to again focus it on the mark. Remove the cube and focus on the table top, observing the additional distance through which the carriage is lowered. From these measurements determine the index of refraction of the glass.

B. Partly fill a hollow glass cube with water, make a similar set of measurements, using pieces of paper pasted on the bottom (inside) of the cube, and floating on the surface of the water as objects, and determine n for water.

C. Repeat part B, using another liquid, e.g., carbon bisulphide.

D. Instead of the glass cube used in part A, use a plano-convex lens with the plane side uppermost, and again determine the value n for glass. N.B. The first reading must be taken with the convex side uppermost so that the plane surface will be the refracting surface when the lens is turned over. How does this result compare with that obtained in part A?

E. Place the lens used in part D on the table with its plane side up for the first reading and down for the second reading. Repeat the measurements and using equation (2) calculate n. Does this value agree with your previous values of n for glass? If not, see whether you can account for the discrepancy.

F. By means of a lens measure or a spherometer determine the value of r, and using this value together with the data obtained in part E, by means of equation (3), calculate the value of n. How does this value of n compare with that found in D.

G. Tabulate the values of the indices of refraction which you have determined along with the corresponding values as given in standard tables.

38B. INDEX OF REFRACTION BY MINIMUM DEVIATION

Read Caswell's *An Outline of Physics*, pp. 392–398.

Preliminary Exercise. If the student has not performed Experiment 38A he may perform the preliminary exercise for that experiment.

The Principle of the Experiment. When light is passed through a prism the light is refracted and thereby deviated through an angle which depends upon the magnitude of the refracting angle of the prism, the index of refraction of the material of the prism and the angle of incidence of the ray entering the prism. Whenever the angle that the incident ray makes with the surface of the prism is equal to the angle which the emergent ray makes with the opposite surface, the angle of deviation is a minimum.

When this condition is satisfied the angle of incidence $i = \frac{1}{2}(A + D)$, where A = refracting angle of the prism and D = angle of minimum deviation. Furthermore, the angle of refraction $r = \frac{1}{2}A$. But, according to Snell's law of refraction, the refractive index of the material of the prism is given by $n = \sin i/\sin r$, whence

$$n = \frac{\sin \frac{1}{2}(A + D)}{\sin \frac{1}{2}A}. \tag{1}$$

The spectrometer is an instrument especially well adapted to the measurement of the angles of the prism and the angle of deviation of a ray of light. It consists of a collimator, a prism table, and a telescope which can be rotated in a horizontal plane about the vertical line passing through the center of the prism table as axis. The angular position of the telescope is read on a divided circle with vernier scale. The collimator consists of a tube with a slit at one end and a lens at the other, so situated that light leaving the slit after passing through the lens and over the prism table will enter the telescope. (See Fig. 24, page 160.)

Work to be Done. A. Focus the telescope on a distant object. During the remainder of the experiment exclude as much daylight as possible. Place a Bunsen burner, fitted with an attachment by which a salt solution may be sprayed into the flame, a few inches in front of the collimator slit, the edges of which ought to be in focus. The Bunsen burner should be adjusted to give as colorless a flame as possible when no solution is being sprayed into

it. Close the slit until further closing causes it to become indistinct. Place a prism on the table so that one of its edges is towards the collimator and clamp the table. Note the number of the prism. Find the positions of the telescope when the cross-hairs coincide with the images reflected from the sides of the prism which meet in this edge. It is advisable to cover the third side with a piece of paper or cardboard. If an image is too high or too low to be seen in the telescope, the table needs adjustment. In such cases it is best to consult the instructor. Prove that the angle of the prism is equal to half the angle through which the telescope must be rotated when it is moved from one image to the other. In this way measure all three angles of the prism. How closely does the sum of these three angles approach 180°? If the sum does not come within the limits of experimental error, repeat your measurements. Divide any small discrepancy among the angles so as to make the adjusted values add to 180°.

B. Unclamp the table and turn it until a side of the prism is toward the collimator. Find the refracted image of the slit in the telescope. Turn the table slightly and notice the direction in which the telescope must be moved to keep it on the image. Keeping the image of the slit in the field of view of the telescope, turn the table so as to diminish the deviation of the beam. Thus find the position of the telescope when the cross-hairs coincide with the *least deviated position of the image of the slit.* Remove the prism and find the undeviated position of the image. The angle between these two positions is D. From equation (1) calculate n. If time permits repeat, using another angle of the prism. How closely do the values of n agree?

39. FORMATION OF IMAGES

Read Caswell's *An Outline of Physics*, pp. 388–392, 398–408.

The Principle of the Experiment. The formation of the image of an object by an optical instrument involves the separation of a part of the beam of light coming from the object from the remainder of the light. For this reason an "aperture" plays an important part in the formation of images. In addition to this function, which is shared alike by pinholes, mirrors, and lenses, the latter collect larger amounts of light than an unaided eye or a pinhole, and also affect the light in such a way that the images are formed at different places from where they would be formed by a pin hole alone.

With suitable conventions regarding the signs of the quantities involved, the relation between the distance u of an object from a lens or mirror, the distance v of the image, and the focal length f, is given by the equation

$$\frac{1}{u}+\frac{1}{v}=\frac{1}{f}. \tag{1}$$

Work to be Done. A. Make a pinhole near the center of a piece of cardboard. Hold the cardboard close to an incandescent lamp with the hole opposite the center of the filament. Hold a sheet of paper parallel to the cardboard but on the side away from the lamp. See whether an image of the filament is formed on the paper. Vary the distance of the cardboard from the lamp, also the distance of the paper from the cardboard. Record the various appearances of the patch of light as seen on the paper under the different conditions.

B. Enlarge the hole until it is about 3 mm. in diameter and repeat the operations of part A. Again record the appearance of the patch of light noting any changes which you observe from those of the preceding tests. Repeat several times, increasing the size of the hole each time and noting the changes seen in the patch of light. Finally, make a new pinhole five or six cm. away from the large hole you now have, and make a direct comparison of the two patches of light coming through the two holes. See whether you can make a statement relating the shape of the patch of light, the size of the hole and the distances between the

lamp and the cardboard and between the paper and the cardboard.

C. Replace the cardboard by a small convex lens and repeat the operations of part A. Do this carefully and note the changes in appearance of the patch of light formed on the paper in the various positions of lens and paper. Does the lens function in a manner similar to the pinhole? Explain. Could you look upon a pin hole as a lens? If so, what advantages are gained by using a lens? Perhaps you can answer this question in terms of the brightness of the image formed, its size and convenience of location.

D. Place a convex lens on an optical bench and locate the image of the lamp as carefully as you can. Do this for several distances of the object. Record the values of u and v for each case, and using equation (1) calculate the values of f. How closely do these values agree?

Hold the lens so that the image of a distant object such as a tree is formed on a sheet of paper and measure the distance of the paper from the lens. Is this distance the same as that calculated for f? If so, the image distance for a distant object is the same as the focal length of the lens. Would equation (1) lead you to expect this result? Give reasons for your answer.

E. Try using a concave lens as in the preceding paragraph. What difficulties do you encounter? Can they be accounted for by assuming an image formed on the same side of the lens as the object? Look through the lens at the sheet of paper or a page of print. Can you see an image? Where does it appear to be located? How does its size compare with that of the object? Can you find a position where it appears larger than the object? See whether you can find a convex lens such that when its surface is placed in contact with the concave lens the two together have the same effect as a piece of plane glass. If you can, the two have the same focal lengths, but since the one "neutralizes" the other, the focal lengths are given different signs.

F. A "linen tester" is a convex lens of short focal length just within the focus of which is a rectangular opening in a brass frame. Look at the frame through the lens and note that the image is formed in a manner similar to that of the concave lens. Is the image larger in appearance than the opening when seen without the lens? In both of these cases the image is said to be "virtual," while in the case of the pinhole and earlier cases the convex lens, the image was said to be "real."

G. Mount the linen tester in a clamp with the axis of the lens vertical and with the lens about 25 cm. above the scale on a ruler

laid on the table top. Hold a piece of cloth against the rectangular opening and observe that the cloth is clearly seen but much magnified. Then hold the cloth at the same distance from the eye, but without the lens in between, and note that it appears the same size but cannot be seen distinctly. The lens enables one to bring the object closer to the eye, thus subtending a larger angle at the eye, and still have it clearly seen.

H. Look through the lens at the rectangular opening (and the ruler which is out of "focus") and at the same time look at the ruler directly with the other eye. Hold the ruler so that it is clearly seen when viewed directly. Let the ruler be lying lengthwise of the opening, and note what length of the ruler is seen in juxtaposition with the opening in the frame. Measure the length of the opening and divide the length of the portion of the ruler seen through the opening by the length of the opening. The quotient is the magnification produced by the lens.

40. PHOTOGRAPHY

Read Caswell's *An Outline of Physics*, pp. 398–408. See also one of the following: Neblette's *Photography, Its Principles and Practice*, Roebuck's *The Science and Practice of Photography*, Watkins' *Photography, Its Principles and Applications*, and *Photography as a Scientific Implement* (Applied Science Series).

The Principle of the Experiment. The essential parts of a camera are (1) a convex lens, or lens combination, (2) a photographic plate, or film, upon which an image of the object is formed by the lens, (3) a bellows, or dark box, to shut off extraneous light, (4) except in cameras of fixed, or universal, focus a focussing device to adjust the length of the bellows so that the image formed by the lens shall be sharply focussed on the plate, (5) a diaphragm to vary the size of the aperture of the lens, and (6) a shutter, which when open admits light to the photographic plate, thereby "exposing" it.

The amount of light reaching the photographic plate in a given length of time depends upon the "numerical aperture" of the lens. This quantity is sometimes called the "speed of the lens." It is the ratio of the diameter of a lens to its focal length. In commercial practice this quantity is denoted thus: $F/6.3$, $F/8$, etc. $F/6.3$ means that the focal length of the lens is 6.3 times its diameter, $F/8$ means that the focal length is 8 times its diameter, and so on. The diaphragm may be used to reduce the effective numerical aperture, since it reduces the effective diameter of the lens. The scale attached to the diaphragm is calibrated in either the "F" system or the "U.S." system. In the F system the numbers correspond to those given above and are inversely proportional to the diameters of the opening, but in the U. S. system they are inversely proportional to the areas of the opening, and so are directly proportional to the proper times of exposure. For comparison the corresponding readings on the two scales are given below:

F	4.00	5.66	8.00	11.3	16.0	22.6	32.0
U. S.	1.	2.	4.	8.	16.0	32.	64.

The proper time of exposure depends upon four factors:

1. The intensity of illumination,
2. The nature of the object being photographed,

3. The aperture, or diaphragm opening, used,
4. The sensitiveness of the photographic plate or film.

The photographic plate is coated on one side with an emulsion consisting of exceedingly minute particles of silver bromide ($AgBr$) held in colloidal suspension in gelatine. When the silver bromide grains are exposed to light and the plate is "developed" they behave differently from those which are not so exposed. The gelatine on the plate consists of a large number of minute cells and when the plate is put into a solution, called a "developer," the solution quickly penetrates into these cells and from them more slowly into the gelatine itself. When the developer reaches a grain of the silver bromide it dissolves it, or tends to dissolve it, the process stopping when the solution becomes saturated with silver. However, if the grain has been exposed to light, the metallic ion, i.e., the silver, will be precipitated out of the solution as metallic silver, and the halogen ion, i.e., the bromine, will combine with the developer to form a new salt. For example, if a hydrochinon developer is used, sodium bromide ($NaBr$) is formed. After the silver from the grains of the silver halide that were exposed to the light has been precipitated in the form of metallic silver, the remaining silver bromide and the salts resulting from the action of the developer are removed in the process of "fixing" and washing the plate.

The principal constituent of the "fixing bath" is usually a solution of sodium thiosulphate, commonly called "hypo." It combines with the silver bromide and the developer residues to produce salts which are soluble in water and so may be washed out of the gelatine on the plate, leaving only metallic silver in the plate.

After being developed the plate shows varying degrees of opacity, or "density." The density of the developed plate, which is called a "negative," is proportional to the logarithm of the time of exposure. The term "negative" is derived from the fact that light objects appear dark in the "negative," and vice versa. Hence, if a series of exposures are made with the ratio of the times for two successive exposures always the same, the resulting densities will vary in uniform steps. However, if a negative is very much over-exposed, a reverse process may set in and a negative with an excessively long exposure may even be changed to a "positive."

A slight over-exposure may be corrected to a limited extent by under development of the negative, and vice versa. Various developers are on the market which require particular treatment.

When a plate is properly exposed and developed the denser portions of the negative, i.e., the higher lights in the picture, should show plainly when the negative is viewed from the glass side, commonly referred to as the "back of the plate."

In the process of fixing, the fixing bath acquires silver salts. If the fixing solution contains less than 2 per cent of silver salts, i.e., 20 gm. per liter, the plate is properly fixed when the opalescent coating disappears from the back of the plate. But if the fixing bath contains more than this amount, the plate should be removed and placed in a fresh, or nearly fresh, fixing bath. To leave the plate longer in the first solution may ruin it. In practice it is advisable to use two fixing baths, one fresh and one which has been used. Fix the plate in the used bath until the opalescent coating has disappeared, unless this is unduly delayed and then leave it for five minutes in the fresh bath.

After the plate is removed from the fixing bath it should be thoroughly washed in water at a temperature not above 20° C. If the water is too warm, the gelatine film may swell and be injured.

Work to be Done. A. Procure from the store room a camera and tripod, focussing cloth, plate holder loaded with two plates, and a negative envelope. Before leaving the laboratory make sure you understand the operation of the camera, how to set it up, open and close it, focus it, and how both the shutter and diaphragm work. The slide covering the plate in the plate holder is divided into five strips by straight lines.

Select an outdoor view which has an approximately level sky line with some objects close at hand and a hill or some distant object for comparison. Set up and focus the camera, being careful that the sunlight does *not* strike the tube around the lens. Set the "diaphragm lever," under the lens if in the U.S. system at 64, if in the F system, at 32, and the "shutter lever" at T. T stands for "time exposure" and one movement of the operating mechanism is required to open the shutter and another to close it. Reverse the slide covering the plate in the plate holder in the side next the lens, and pull it out to the first line, expose the plate 20 seconds by the watch. Draw the slide to the second line and expose for 4 seconds. Draw the slide to the third line, and set the shutter lever at B. B stands for "bulb exposure" and means that the shutter is held open as long as the bulb is pressed, but no longer. Expose for 0.8 second as nearly as possible. Draw the slide to the fourth line and expose as short a time as possible, (if the shutter has numbers on it set the shutter lever at 1/5 for

this exposure). Remove the slide, set the shutter lever at 1/25 second and expose. Insert the slide and return to the dark room. The strips will have had 25, 5, 1, 1/5, and 1/25 seconds exposure, respectively.

Write your name on one end of the plate with a soft lead pencil (not indelible) and develop it according to the directions of the instructor. Which strip gives the best results?

B. Make a picture of any view you desire using the information obtained in part A to assure the correct time of exposure. Leave the negative envelope, with name and data, near the place where the plates are dried so that when dried the plates may be placed in it.

C. At the beginning of the next laboratory period, or at some other time when the laboratory is open, get from the store room some sheets of photographic paper. In the dark room by a safe light write your name on the backs of the sheets with a lead pencil, and make and develop prints of your negatives according to the directions of the instructor. These prints when finished and dry will be part of the notes for your experiment.

41. MICROSCOPES

Read Caswell's *An Outline of Physics*, pp. 401–408, 411–413.

The Principle of the Experiment. A simple microscope consists essentially of a short focus convex lens with the object to be examined placed nearer to the lens than its principal focus, so that a virtual image is formed at the distance of most distinct vision from the eye. If the eye is close to the lens, this distance may be regarded as the image distance measured from the lens. The magnification produced is the ratio of the size of the image to the size of the object, and this ratio is the same as the ratio of the image distance to the object distance. If we denote the distance of most distinct vision by D, the object distance by u, and the focal length by f, the magnification is given by

$$M = \frac{I}{O} = \frac{D}{u} = \frac{D}{f} + 1. \tag{1}$$

The compound microscope has a very short focus convex lens which is used as the "objective." The object is placed slightly farther away from the lens than its principal focus. This gives an enlarged real image of the object. The magnification given by the objective is

$$M_0 = \frac{I_0}{O} = \frac{v_0}{u_0}, \tag{2}$$

where u_0 and v_0 are related to the focal length of the objective by the equation

$$1/u_0 + 1/v_0 = 1/f_0. \tag{3}$$

The image formed by the objective becomes the object for a short focus convex lens used as a simple microscope. The latter lens is called the eyepiece. Therefore the total magnification given by the compound microscope is

$$M = \frac{v_0}{u_0}\left(\frac{D}{f} + 1\right). \tag{4}$$

Work to be Done. A. *Simple Microscope.* Determine the distance of most distinct vision for your eye by finding the shortest distance from your eye to a printed page on which the letters can

be seen with perfect distinctness for several minutes without undue strain on the eye. Usually this is about the distance at which you naturally hold a small object when you wish to examine it carefully.

Obtain a very short focus convex lens and measure f. This may be done by the method of parallax. Mount the lens on an optical bench and view a distant object, such as a tree, through it. Locate the image of the object by mounting a screen with an opening having cross-hairs stretched across it upon the optical bench and moving the cross-hairs toward and from the lens until such a position is found that the image and the cross-hairs appear to move together as your head is moved from side to side. If the image and the cross-hairs do not coincide in position you can determine which is nearer to the eye by holding two objects in line in front of the eye and observing their relative motion as the head is moved from side to side.

The image of the distant object may also be sharply focussed upon a white screen. In either case the distance from the image to the lens is the focal length of the lens.

With the eye close to the lens look through it at an object, such as a celluloid scale. Find the least distance of the scale from the lens for which the image remains distinct. The image ought to appear to be at the distance of most distinct vision as in the case of the object above. Calculate the distance of the image from the lens, and compare this value with the distance for most distinct vision already obtained. Let this distance be D. Using equation (1) calculate M. Check your computed result by looking through the lens at a celluloid scale with one eye, and with the other eye looking directly at a similar scale held at a distance D from the eye in such a way that the scales seen by the two eyes are superimposed. The number of centimeters of the scale seen directly which seem to coincide with one centimeter of the scale seen through the lens is the magnification M.

B. *Compound Microscope.* Procure another short focus convex lens to be used as the objective of a compound microscope and measure its focal length as in part A. Set a scale or piece of wire gauze at one end of the optical bench, and place the objective close to it so that an enlarged real image will be formed near the other end of the bench. Locate this image with the aid of cross-hairs, and measure u_0 and v_0. Use the lens previously used in part A as an eyepiece to view this image. Using equation (4) calculate the magnification produced by the compound microscope. Check this value experimentally after the manner of part

A. The image seen through the eyepiece should be at your distance of most distinct vision. Note that the image can still be seen clearly through the eyepiece when the image formed by the objective is at the principal focus of the eyepiece. How is the magnification related to the length of the microscope tube? to the focal length of the objective?

C. Draw a diagram of the compound microscope, approximately to scale, showing the positions of objective, eyepiece, cross-hairs, images formed by both lenses, and the eye. It is advisable to use cross-section paper. Draw two rays from a point in the object to the eye, hatching the region between them. Assuming that the object is represented in your diagram by an erect arrow and its image formed by the objective by an inverted arrow, it will be convenient to choose the tip of the object arrow as the point from which the rays are to emanate. The two most convenient rays to use may be found by drawing two lines as follows: One from the bottom of the objective through the tip of the objective arrow image to the eyepiece and prolonged after proper refraction to the point in the object and to the eye. The second from the bottom of the eyepiece through the tip of the image to the objective and prolonged to the point in the object and to the eye.

42. TELESCOPES

Read Caswell's *An Outline of Physics*, pp. 401–408, and 411–415.

The Principle of the Experiment. The general lens formula is

$$\frac{1}{u}+\frac{1}{v}=\frac{1}{f}. \tag{1}$$

For distant objects $v = f$, and when u is approximately equal to f, the image is distant.

All telescopes have long focus convex lenses of relatively large diameter for objectives. The image of a distant object is formed in the principal focal plane of the objective. The astronomical and terrestrial types have simple microscopes, or equivalent combinations, for eyepieces, while the Galilean (the common field or opera glass) has a very short focus concave lens as an eyepiece. In addition the terrestrial telescope has a convex "erecting lens" placed between the image formed by the objective and the eyepiece. It is customary in practice to focus the eyepiece of a telescope for light in which the rays are parallel, i.e., the image is far away. In these cases the image should appear to be at a distance of several meters. When this adjustment has been made the image formed by the objective must be in the principal focal plane of the eyepiece, and the principal focus of the eyepiece must coincide with that of the objective. The telescope magnification is defined as the ratio of the visual angle subtended at the eye by the image to that subtended by the object. The magnification produced by a telescope is given by the equation

$$M = F/f, \tag{2}$$

where F and f are the respective focal lengths of objective and eyepiece.

Work to be Done. A. Determine the focal length of a rather long focus convex lens of five or more centimeters diameter as in Experiments 39D or 41A. Likewise determine the focal length of a short focus convex lens. Using the former as objective and the latter as eyepiece build up on an optical bench an astronomical telescope, and view a distant object such as a tree. Better results may be obtained if the light passes from the ob-

jective through a pasteboard, or other tube of about the same diameter as the objective on its way to the eyepiece.

Calculate the magnification produced by means of equation (1). See if you can check this value approximately by superimposing the image as seen through the telescope by one eye upon the object as seen directly by the other eye.

B. Convert the astronomical telescope of part A into a terrestrial telescope, using a short focus convex lens as an "erecting lens." Place the erecting lens twice its focal length behind the image formed by the objective.

C. Construct a Galilean telescope, replacing the eyepiece used in part A by a concave lens of about the same focal length. The focal length of a concave lens can be found by using it to neutralize a convex one of known focal length.

43. A STUDY OF A STEREOPTICON

Read Caswell's *An Outline of Physics*, pp. 423–425.

The Principle of the Experiment. A stereopticon consists of (*a*) a source of light, (*b*) a condensing lens, or lens system, which serves to illuminate a lantern slide and direct the beam of light through the projecting lens, (*c*) a slide, held in a slide-holder which is placed as near the condenser as possible, and (*d*) a projecting lens, or lens system, which forms an image of the slide upon the screen. In your experimental assembly the different parts are to be clamped to a horizontal steel rod, and for successful operation of the stereopticon it is necessary that the source of light, the center of the condenser, and the center of the projecting lens shall lie in the same straight line.

The condensing lens system usually consists of two plano-convex lenses of short focal length turned with their convex faces toward each other. Why are two lenses used, and why are they arranged in this way? The light from the source should be made to converge to a focus in the projecting lens system, or if only one lens is used as a projecting lens, the beam should converge to a point very close to the projecting lens. Why is this necessary? The distances between the slide and the projecting lens, and between the projecting lens and the screen upon which the picture is being shown, must be related to the focal length of the projecting lens by the ordinary lens formula, viz.,

$$1/u + 1/v = 1/f. \qquad (1)$$

Work to be Done. A. Draw a diagram of the equipment to be used, showing a longitudinal section of the apparatus, i.e., from source of light to picture screen, and indicating the cross-section of the beam of light by dotted lines.

Clamp a concentrated filament, nitrogen-filled tungsten lamp, which is provided with a hood, to that end of the steel rod farthest away from the screen. Next to it on the rod, nearer the screen, clamp a condenser, then a slide-holder, and nearest the screen, a projecting lens.

Place the slide-holder, with a slide inserted, as near the condenser as is convenient. The principal object here is to have the slide well illuminated by the beam of light.

Adjust the projecting lens so that a sharp image of the slide

falls upon the screen. It is probable that not all of the image will be well illuminated at this stage of the experiment.

Move the lamp back and forth along the steel rod until the field, i.e., the picture screen, is best illuminated. In securing good illumination, note that the items assembled must be centered and aligned so that the light passes through the center of the projecting lens. Note also that when final adjustment is obtained the minimum cross-section of the beam is at or near the projecting lens.

B. Measure the dimensions of the image and the corresponding part of the lantern slide, and determine the magnification. Measure the distance from the slide to the projecting lens, and the distance of the latter from the screen, and calculate the focal length of the projecting lens from equation (1). What relation exists between u and v and the magnification produced by the stereopticon?

C. Answer the following questions: How can the field of view be enlarged? What adjustment would you make to eliminate a colored center in the field? a colored edge? What adjustment would you make to focus the image more sharply?

D. Replace the lamp previously used by a right-angled carbon arc which is connected to the 110-volt D.C. mains, taking care to see that a resistance of considerable current-carrying capacity is in series with it. Connect it so that the horizontal carbon is positive and observe the behavior of the stereopticon for some minutes. Reverse the polarity and again observe its behavior. What are your conclusions? Replace the D.C. current with A.C. and observe the result. What are your conclusions?

44. A STUDY OF A LENS AND ITS DEFECTS

Read Caswell's *An Outline of Physics*, pp. 401–408, 415–419, 425–429.

The Principle of the Experiment. A lens made of one material with spherical or plane surfaces, but without flaws in the material itself nevertheless suffers from a number of defects. Because of its spherical surfaces the focal length of the edge of the lens is different from that of the center, giving rise to spherical aberration. The refractive index of the material is different for different colors, giving rise to chromatic aberration. The oblique passage of light through the lens makes the comparative curvature of the surfaces with reference to light different in different directions, giving rise to astigmatism.

In this experiment the student is expected to become familiar with these defects of an uncorrected lens, and incidentally to make use of the lens formula

$$1/u + 1/v = 1/f, \tag{1}$$

where u = object distance (positive for real objects, negative for virtual objects), v = image distance (positive for real images, negative for virtual images), f = focal length (positive for convex lenses, negative for concave).

Work to be Done. **A.** Mount a rather long focus convex lens on the optical bench and determine its principal focal length. This can be done quite accurately by viewing a distant object, such as a tree, through the lens and locating the image by parallax with the aid of cross-hairs. When the image and cross-hairs coincide they will appear to move together as the head is moved from side to side. If they do not coincide determine which is nearer to the eye by holding two objects in line in front of the eye and observing their relative motion as the head is moved from side to side. Using an incandescent lamp, having a straight filament, locate its image for several positions in this way. Measure the object distance u and the image distance v in each case and calculate f from equation (1). How do the various values of f agree? Determine the magnification produced by the lens for one object distance by means of equation

$$M = I/O = v/u.$$

On a sheet of rectangular cross-section paper plot the various values of u along the horizontal axis and the values of v along the vertical axis. Draw a straight line from each value of u to the corresponding value of v. These lines should intersect at the point whose coordinates are $(u = f, v = f)$. Determine the best value of f from your chart.

B. Place a piece of cobalt blue glass which transmits two colors between the incandescent lamp and the long focus convex lens used in part A and observe the images formed. If this glass is not available, use first a piece of blue glass and then a piece of red glass. Let the lamp be considerably farther from the lens than its principal focus. Which of the two colored images is the nearer to the lens? Which color is refracted most?

C. Mount the lens used in part A on an optical bench in a frame which may be rotated about a vertical axis. Place the incandescent lamp so that its image will be formed about 80 cm. from the lens when the axis of the lens is parallel to the bench. With the filament in a vertical position rotate the lens slightly about the vertical axis and examine the image by moving a screen, which may consist of a piece of white paper with an opaque object behind it, from the lens to the original position of the image. Can you find a position where vertical lines are sharply focussed? Rotate the lens through several different angles. How does the rotation of the lens affect the position of the image?

Repeat with the filament in a horizontal position. Can you find positions where horizontal lines are sharply focussed? How are these positions related to the positions for vertical lines when the angle of rotation of the lens is the same in both cases? What is the image of a point where vertical lines are sharply focussed? Where horizontal lines are sharply focussed?

D. Mount a short focus convex lens on an optical bench in a frame arranged so that either the center or the edge of the lens can be covered. A plano-convex lens about 4 in. in diameter and 6 in. focal length is very well-adapted for use in this part of the experiment. Determine the position of an image using only the center of the lens and calculate f. Repeat for the edge of the lens. Is there any difference between the focal lengths? If so, which is the shorter? If a plano-convex lens is available, test it with the plane side toward the object and also the convex. Which is further from the lens, the image or the object? In which case is the aberration most pronounced? Is aberration least when the deviation is least?

45. IMPULSE AND MOMENTUM

Read Caswell's *An Outline of Physics*, pp. 184–189, 433–437.

The Principle of the Experiment. From Newton's second law of motion, $F = ma$, where F is the force acting upon a body of mass m, expressed in absolute units, and a is the acceleration produced. Substituting for a its value $(v_2 - v_1)/t$, where v_1 and v_2 are the speeds of the body at the beginning and end of the interval of time t, we obtain

$$Ft = m(v_2 - v_1), \tag{1}$$

If a mass m of a fluid strikes an object in a unit of time and has its speed changed from v to 0, $t = 1$, $v_1 = v$, $v_2 = 0$, and equation (1) becomes

$$F = mv. \tag{2}$$

A horizontal brass vane B that is free to rotate about a vertical axis A has a small reentrant funnel F soldered to it as shown in Fig. 19. C is a counterpoise adjusted to eliminate friction in the

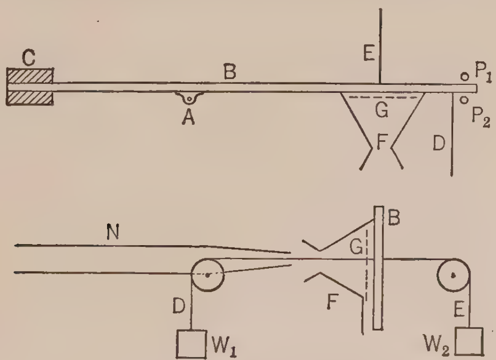


Fig. 19.—Impulse Apparatus.

bearing at A. D is a cord at right-angles to the vane, and passing over a pulley to which a weight W_1 is attached. E is a similar cord to which a weight W_2 is attached, also at right-angles to the vane. P_1 and P_2 are pins close to the vane to prevent it from swinging around.

N is a nozzle from which a stream of water is directed into the funnel F. G is a piece of wire gauze in front of the vane to prevent

the water from being reflected out of the funnel. When properly adjusted, the water should drop quietly out of the funnel through an opening below G as shown in the lower part of Fig. 19.

The weights W_2 and W_1 are adjusted so that the vane rests between the pins P_1 and P_2 without touching either one of them. When a stream of water is directed into the funnel equilibrium is destroyed, and the weight W_2 should be reduced until the initial condition is restored. The amount by which the weight W_2 is reduced, when expressed in dynes or poundals, is the force F in equation (2), and the mass of water which passes through the funnel in one second is m. If the cross-sectional area of the nozzle is A, the speed of the water is given by

$$v = m/DA, \tag{3}$$

where D = density of the liquid.

Work to be Done. Adjust the weights W_1 and W_2 as indicated in the preceding paragraph and turn on water from the water faucet through the nozzle N, to be sure that the weights are large enough. If the weights are too small the vane will strike the pin P_2 when the weight W_2 is entirely removed. If the weights are too small, turn off the water and readjust W_1 and W_2. After W_1 and W_2 are suitably adjusted, regulate the stream of water and catch the water issuing from the funnel in a vessel, noting the length of time required to collect it, also reduce the weight W_2 until the vane will again rest between P_1 and P_2 without touching either of them. If the total mass of water collected is M and the time taken to collect it is t, $m = M/t$.

Determine of the area A of the orifice in the nozzle.

Using equation (3) calculate the speed v of the water. Put the values of m and v into equation (2) and calculate F. Compare this value with the change in the weight W_2 expressed in the proper units.

Instead of assuming the value of the acceleration of gravity in changing grams weight into dynes, or pounds weight into poundals, the change in the weight W_2 may be expressed in grams weight (or in pounds weight), while the value of the force calculated from equation (2) will be expressed in dynes (or poundals). The ratio of these two numerical values of F will be the numerical value of g, the acceleration of gravity, expressed in the same system of units.

Make several determinations of the speed of the water and the force exerted upon the vane with the stream of water regulated in different ways. Arrange a table of observed and computed quantities, including the computed values of g for each case.

46. SPEED OF A BULLET BY THE BALLISTIC PENDULUM

Read Caswell's *An Outline of Physics*, pp. 436–440.

The Principle of the Experiment. When a bullet is fired into an object it exerts a very large and variable force upon it for a very short space of time. Neither the force nor the time can be measured directly and so we resort to the principle of momentum. If the body which is struck is at rest and free to move, the bullet will impart to it a speed V, which is related to the speed v of the bullet, the mass m of the bullet, and the mass M of the body by the following equation of momentum:

$$mv = (m + M)V. \tag{1}$$

An oblong block of wood is suspended by two bifilar suspensions and has a cavity in one end filled with a plastic material to receive the bullet. When a bullet is fired into the end of the block, it swings as a pendulum, and the height h through which it rises is the same as that through which it would have to fall to acquire the velocity imparted to it by the bullet. Hence

$$V = \sqrt{2gh}, \tag{2}$$

where g = acceleration of gravity. Let the vertical distance between the parallel horizontal planes containing the upper and lower ends of the suspensions be L and the length of the arc through which the pendulum swings be d, then

$$h = \frac{d^2}{2L}\cdot \tag{3}$$

From equations (1), (2), and (3) we find that

$$v = \frac{(m + M)d}{m}\sqrt{\frac{g}{L}}\cdot \tag{4}$$

Work to be Done. A. An "air-rifle" and a supply of screened shot are provided. Weigh a number of shot, say 50, and determine m. Also determine M and L. Holding the muzzle of the rifle about 20 cm. from the block, fire a shot into it, and with the aid of a meter stick placed on the edge of the table parallel to the path of the block, determine d. Repeat several

times and use the average value of d. Substitute these values of m, M, d, g, and L in equation (4) and calculate v.

B. Hold several thicknesses of cardboard between the muzzle of the rifle and the end of the block, and fire the shot through the cardboard into the block and again calculate v. Estimate the number of thicknesses of cardboard which will just stop the bullet. Try this number and see whether your estimate is correct.

C. Taking care to see that there is no danger of injuring any one with the rebounding shot, fire the shot against the opposite end of the block from the cavity. Since the block is hard the shot will not penetrate it far enough to become imbedded in it but will rebound from it. Calculate the momentum imparted to the block and compare it with the momentum imparted to it in part A. How do you account for the difference?

47. UNIFORM CIRCULAR MOTION

Read Caswell's *An Outline of Physics*, pp. 474–483.

The Principle of the Experiment. Every boy is familiar with the fact that if a pebble is whirled in a sling it manifests a tendency to fly off and a force is required to be exerted toward the center of the circle in order to hold it in its path. Mud flies off a rapidly-moving vehicle tire while it adheres to a slowly-moving one. This is because the force of adhesion is sufficient to hold the mud in its curved path in the latter case but not in the former. The mud is most apt to fly off when near the top of the wheel since it is moving most rapidly at that point.

It can be shown that if a body is moving in an arc of a circle of radius r, with a speed v, it is experiencing an acceleration directed toward the center of the circle, the magnitude of the acceleration being given by the equation

$$a = v^2/r. \tag{1}$$

Since $F = ma$, where F is the force in dynes required to give an acceleration a in cm./sec^2. to a mass of m grams, it follows that

$$F = mv^2/r. \tag{2}$$

If the body is making n revolutions per second, $v = 2\pi rn$, whence

$$F = 4\pi^2 rn^2 m. \tag{3}$$

Two forms of apparatus are available for this experiment, in which the foregoing equation may be put to the test. Incidentally, we may also use this as a means of determining the value of the acceleration of gravity, g.

In the first form of the apparatus two small cylinders are free to slide along a pair of rods which may be rotated rapidly around a vertical axis. By means of cords the cylinders are attached to a heavy collar which slides up and down on the vertical axis. The speed of rotation is regulated so that the collar is maintained in equilibrium, the force of gravity acting on the collar being just sufficient to keep the two small cylinders moving in a circle. This apparatus possesses one very serious defect. If the speed of revolution is made slightly too great, the small cylinders are not held in with sufficient force and so move out from the axis, thereby

increasing r, which results in still further increasing the force required to hold the cylinders in the circular path. If the speed of revolution is too small the converse effect occurs. Consequently, if the apparatus were frictionless, it would be practically impossible to obtain satisfactory results with it. This is a case of unstable equilibrium.

With this apparatus when equilibrium is attained, the force in dynes holding the cylinders in a circular path is Mg, where M = mass of the collar in grams, and g = acceleration of gravity (about 980 cm./sec^2.). Then

$$Mg = 4\pi^2 rn^2 m. \tag{4}$$

It is, therefore, necessary to determine the number of revolutions made by the apparatus per second when equilibrium is attained, the total mass of the cylinders, i.e., m; the mass of the collar M; and the radius of the circle in which the cylinders move. This may be found by noting the position of the collar on the vertical shaft when the apparatus is rotating and lifting the collar to this position by pulling the cylinders out along the parallel rods when the apparatus is at rest, then measuring the distance between their centers. In this experiment care must be taken to see that the collar is neither supported by nor held down by the frame of the apparatus, but is just supported by the cords.

In the second form of the apparatus a single large mass sliding freely between three guide rods is rotated about a vertical axis. The force to constrain it to travel in a circle is supplied by a spring. An adjustment is provided for varying the tension in the spring. As the speed of rotation is increased, the mass moves outward between the guide rods and engages a pointer, raising the tip of the pointer until it is opposite the sharp edge of an index at the axis of rotation. No matter what the speed of rotation, it is always possible to see the tip of the pointer and the index clearly.

In order to determine the force exerted by the spring in holding the moving mass in its circular path the apparatus is suspended from a clamp, with the axis of the spring in a vertical position, and weights are attached until the elongation of the spring is the same as before. This is shown by the position of the tip of the pointer opposite the index. The stretching force includes not only the weights attached to the apparatus to stretch the spring but also the weight of the mass which is whirled. The apparatus is so constructed that the effect of the mass of the spring and of the pointer may be neglected. Equation (4) applies to this case also, M being the mass in grams required to stretch the spring

when suspended, and m the mass which was rotated. The radius of the circle in which the mass m moves may be determined while the apparatus is suspended from the clamp by measuring from the axis of rotation to both the upper and lower sides of the mass m, and taking the average value.

Work to be Done. A. Mount the apparatus on a suitable rotator. If the rotator driven by a motor with a friction drive is available, better results can be obtained than with a hand rotator. If the first apparatus is being used, fasten the two cylinders to the cords at equal distances from the axis with the set screws intended for that purpose. If the second apparatus is used, adjust the tension in the spring.

Rotate the apparatus and regulate the speed until the conditions indicated above are satisfied. Record the mass rotated, and the number of revolutions of the apparatus made in a known time. Determine the force in grams required to keep the mass moving in the circle, and determine the radius of the circle.

Calculate g from equation (4).

Repeat the operation a number of times until you secure a set of values which agree within the reasonable limits of experimental error.

B. Readjust the apparatus in the first case by altering the lengths of the cords, or by attaching additional masses to them, in the second case by altering the tension in the spring, and repeat part A.

C. Compute the accelerations of the moving mass in parts A and B from equation (1), or the equivalent equation obtained by substituting $2\pi rn$ for v. Also determine the value of a vectorially by drawing the vectors representing the velocity at two points on the circle, ten degrees apart. In this case the interval of time will be $1/36n$ second, and $a = \dfrac{V_2 - V_1}{t}$.

48. THE CONDITIONS OF EQUILIBRIUM

Read Caswell's *An Outline of Physics*, pp. 474–477, 479–481, 493–498.

The Principle of the Experiment. In order that a body shall be at rest under the action of all the forces acting upon it, two conditions of equilibrium must be satisfied. They are as follows:

First condition of equilibrium: The vector sum of all the forces acting upon the body must be equal to zero.

Second condition of equilibrium: The algebraic sum of all the moments of force, or torques, acting upon the body, taken about any axis, must be equal to zero.

Work to be Done. A. In order to test these conditions of equilibrium, a circular force table is used which is graduated in degrees on its outer edge. Place a small ring over a pin in the center of the force table. Attach three weight hangers to the ring by means of cords passing over pulleys attached to the circumference of the force table. Attach weights to the hangers and adjust them so that the pin is at the center of the ring. Note the angular positions of the pulleys and the weights attached to the strings, including the weight of the weight hanger itself in each case. Draw the vector diagram for the sum of these three forces acting upon the ring.

Repeat this operation for several different positions of the pulleys and different sets of weights on the hangers. How nearly do your force triangles close? If they do not close, how do you account for the discrepancy?

B. Instead of attaching the weights to the small ring as was done in part A, attach them to pegs in a thin disk which has a small hole at its center, through which a pin is thrust into the hole in the center of the force table. The hole in the disk should be somewhat larger than the pin. When the apparatus is properly adjusted, the pin should be at the exact center of the disk. This disk should rest on three small steel balls spaced widely apart and the force table should be leveled so that there is no tendency for the disk to move in any direction before the weights are attached. A sheet of polar coordinate paper is pasted to the upper face of the disk. Attach four weight hangers to pegs at various positions on the disk, and adjust the weights until the pin in the center of the force table is at the center of the hole in the disk, but does not touch. Note the positions of the pegs on the cross-section paper and the points where the cords pass over

the edge of the disk. On a separate sheet of cross-section paper similar to that pasted to the top of the disk, construct a figure similar to Fig. 20.

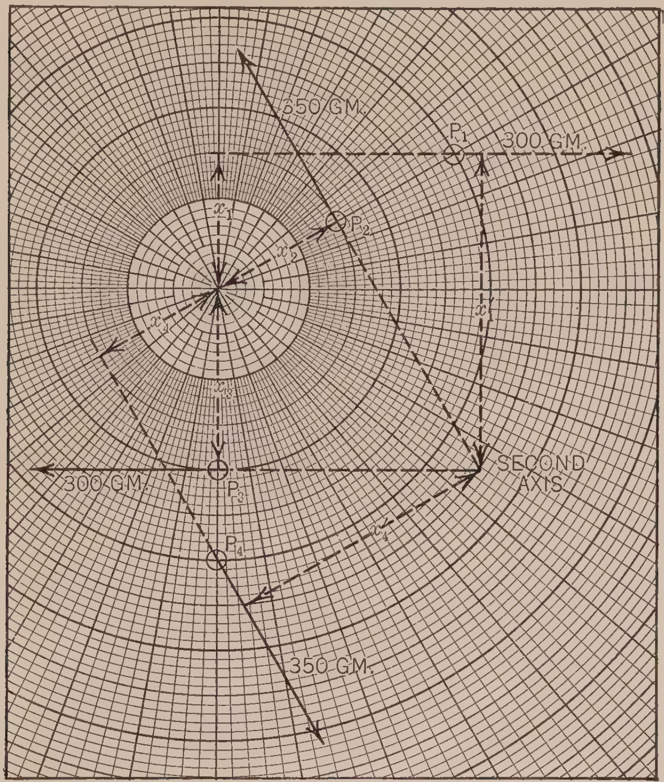


FIG. 20.

Determine the lever arms of the forces as in Fig. 20, taking the center of the disk as the center of moments. Also take some other point near the edge of the disk as the center of moments. Calculate the sum of the moments of the forces about each of these points as axis. How closely do your results add to zero? If they are different from zero, can you account for the discrepancy?

Construct the vector diagram for the four forces used in this part of the experiment. Does your force polygon close? If not, why not?

C. Repeat part B, using different forces and different positions of the pegs and pulleys.

49. THE ANALYTICAL BALANCE

Read Caswell's *An Outline of Physics*, pp. 493–498.

The Principle of the Experiment. The chemical balance consists essentially of a horizontal beam supported at the middle by a "knife-edge" which is slightly above the center of gravity of the beam. Usually the beam is symmetrical with respect to its point of support. At the two ends, and equidistant from its point of support, are two "knife-edges" which carry the two pans of the balance. Usually these two knife-edges and the knife-edge supporting the beam lie in the same straight line.

Assuming that the knife-edges are equally spaced, if the loads on the two ends of the beam are the same, the torques due to the loads offset each other and the action of the force of gravity upon the beam brings the center of gravity directly beneath the point of support. This is the normal position of the balance. But if the load on one end of the beam is greater than that on the other, the corresponding torque is greater and that end of the beam goes down. The line of action of the weight force of the beam then moves to the opposite side of the point of support, giving rise to a counteracting torque. The beam rotates until the torque due to the heavier load is just equal in magnitude to the sum of the torques due to the lighter load and to the weight force of the beam.

If the knife-edges are not equally spaced, an object whose true weight is W may be placed in one pan and counterpoised with standard weights totalling W_1 in the other pan. Then the object is placed in the opposite pan and counterpoised with standard weights totalling W_2 in the first pan. The true weight is given by

$$W = \sqrt{W_1 W_2} \qquad (1)$$

To the beam a vertical pointer is attached, which moves over a scale as the beam rocks. The sensibility of the balance is the deflection of the pointer caused by a difference of unit mass in the loads on the two pans of the balance.

In the experimental balance the beam may consist of an ordinary boxwood meter stick. Any suitable wooden bar may be used. Knife-edges are provided which can be clamped to the beam and their positions may be adjusted vertically. Instead of knife-edges holes may be bored in the beam in suitable positions,

and pins put through the holes to serve as knife-edges. A relatively large mass is attached to the beam directly beneath its point of support. Its distance beneath the point of support may be altered. For the purposes of the experiment this mass constitutes a part of the beam. When it is raised the center of gravity of the beam is raised, and vice versa.

Work to be Done. A. *The Normal Balance.* The knife-edges of the balance are in the same horizontal plane. The outer ones supporting the pans are equidistant from the central one supporting the beam. The center of gravity of the beam is directly below the central support.

(1) Being sure that the beam and pans swing freely, take the reading of the pointer with no load, and again with a convenient small load on one pan. Divide the amount of the deflection by the numerical value of the deflecting load. This gives the sensibility of the balance in terms of the unit of weight employed. Find the sensibility of the balance for a series of different deflecting loads, both right and left. Is the sensibility approximately constant or not? Why?

(2) Similarly find the sensibility of the balance for various deflecting loads when there are initial balancing loads of various amounts on each arm, e.g., 500 gm., 1000 gm., etc. Does the sensibility vary with the load? Why?

(3) Keeping the balance normal, with the same length of arms, but changing the distance of the center of gravity below the central support, determine the sensibility. How is the sensibility related to the distance between the point of suspension and the center of gravity? Why?

(4) Still keeping the balance normal, find the sensibility with the pans at a different distance from the central support. How is the sensibility related to the length of the balance beam? Why?

B. *Variations from Normality.*

(1) With the central knife-edge above the line joining the two end ones, find the sensibility for no load. How does this compare with that previously found with the central one in the same position? Repeat with loads of 500 gm. or 1000 gm. Does the load affect the sensibility? How? Why? What may be the effect of an excessive load on the sensibility of a delicate normal balance? Why?

(2) Repeat with the central knife-edge below the line joining the two end ones. Draw conclusions and give reasons.

(3) Place the knife-edges in the same straight line but with the

end ones at unequal distances from the central support. "Weigh" some object of known weight, e.g., a 500 gm. weight, first on one side of the balance, then on the other. How do the two results compare with the true weight? With their average? With their mean proportional? Why?

C. Make a brief but careful statement of the requisites of a balance for fine analytical work, based on the laws just investigated. How far and in what ways can intelligent use increase the accuracy of results obtained by means of an imperfect balance? What applications have these laws to balances used for rougher commercial weighing?

50. ANGULAR ACCELERATION, TORQUE, AND MOMENT OF INERTIA

Read Caswell's *An Outline of Physics*, pp. 489–500.

The Principle of the Experiment. This experiment is the counterpart in rotary motion of Experiment 19 in linear motion. Angular displacement or distance, angular speed and angular acceleration are, respectively, analogous to linear distance, linear speed and linear acceleration. Torque, or moment of force, is analogous to force, and moment of inertia is analogous to mass (mass being used in the inertia sense). Hence the angle θ through which a body rotates from rest in an interval of time t, under the action of a constant torque G, is given by the equation

$$\theta = \tfrac{1}{2}\alpha t^2, \tag{1}$$

where α = the angular acceleration. Moreover,

$$G = \mathfrak{J}\alpha, \tag{2}$$

where $\mathfrak{J}$ = the moment of inertia.

The value of $\mathfrak{J}$ depends upon the mass and the configuration of the rotating body. Thus, for a flat circular disk rotating about an axis perpendicular to the plane of the disk and passing through its center

$$\mathfrak{J} = \tfrac{1}{2}MR^2, \tag{3}$$

where M = mass and R = radius of the disk.

A rotational inertia apparatus is used in this experiment. A heavy metal disk, with a cylindrical shaft passing through its center perpendicular to the plane of the disk, is mounted horizontally in steel cone pivot bearings. The friction in the bearings is thus reduced to a minimum. The end of a cord may be attached to the rim of the disk with beeswax, or some other soft wax, and the cord then wrapped around the disk several times. A weight is attached to its free end, so that when the weight is released it will fall under the action of gravity and unwrap the cord from the disk, thus setting the disk in motion. One face of the disk is covered with a thin mixture of lampblack and alcohol, applied with a soft brush. As the disk rotates a stylus attached to one prong of an electrically-maintained tuning-fork traces a

wavy spiral on the lampblack surface of the disk. This spiral is produced by moving the stylus from the outer edge of the disk toward its center while the disk is rotating. By marking off the waves in sets of, say, 50, the angular acceleration of the disk may be determined after the method of Experiment 19.

Work to be Done. A. Place the apparatus on a platform about six feet from the floor with the disk projecting two or three cm. beyond the edge of the platform. Remove the disk from its mounting and coat the surface with lampblack. Then replace it, taking care to not injure the bearings as this may result in an undue amount of friction. Attach a string to the rim of the disk either with a little soft wax or by lapping it over itself. Wind enough string onto the rim of the disk so that the string will come free from the disk when the weight attached to the end of it lacks a few centimeters of reaching the floor. Make a loop on the end of the string and attach a 100 gm. weight to it.

Adjust the tuning-fork and stylus so that the stylus bears upon the lampblack surface sufficiently to make a clear trace but not to produce too much friction. Have the stylus near the edge of the disk. Connect the tuning-fork to a suitable battery and set the fork into vibration. Let the 100 gm. weight attached to the string begin to fall, and at the same time begin to move the fork toward the axis of the disk by means of the gear provided for the purpose.

Just before the weight reaches the floor, the string pulls loose from the disk and the disk continues rotating at an almost uniform speed. However, owing to friction the disk is actually decelerated, i.e., given a negative acceleration. To determine this acceleration of the disk after the string is detached, a second determination is made, the disk being set in motion by hand, and the tuning-fork being moved toward the axis as before. Record the number of vibrations the fork makes per second.

Having made the trace remove the disk from the apparatus and stand it upon the end of the cylindrical shaft with the lampblack face uppermost. Beginning where the waves are first far enough apart to be counted separately, mark off the waves in sets of fifty, continuing to that part of the other end of the trace where they are again too close together to be counted.

Replace the disk in its supports, and focus one of the magnifiers attached to the apparatus upon the divided circle engraved near the edge of the disk and the other upon the trace. If the divided circle is not graduated in radians, your angles should ultimately be expressed in radians ($180° = \pi$ radians.). Determine the angular distances between the marks upon the trace.

Prepare a table similar to that shown for Experiment 19, making the necessary computations for finding the angular acceleration α. That part of the trace made after the weight became detached from the disk will give a negative acceleration and should be treated separately. Since the acceleration is diminished by friction, the acceleration obtained from the first part of the trace should be increased by the numerical value of the negative acceleration found from the latter part, or from a second separate determination as indicated above.

B. Repeat part A, using a 200 gm. weight attached to the string, and compare the angular acceleration produced in the two cases. Are they proportional to the forces acting? to the torques acting?

C. Measure the radius of the disk and compute the moment of force for both parts A and B, expressing the results in centimeter-dynes.

D. Weigh the disk, and with a vernier caliper determine its thickness and the length and diameter of the parts of the cylindrical shaft projecting from it. Compute the volume and mass of the disk and of the ends of the shaft. Then compute the corresponding moments of inertia with the aid of equation (3). Add your results to find the moment of inertia of the rotating system.

Having found G, $\mathcal{I}$ and α, separately, check your results with equation (2). Express any differences you find in percent.

E. Compute the moment of inertia of the rotating system, assuming that the shaft is a part of the disk and that the disk is of uniform thickness throughout. What percentage error would have been introduced in part D by using this value of $\mathcal{I}$?

51. SIMPLE HARMONIC MOTION OF TRANSLATION

Read Caswell's *An Outline of Physics*, pp. 507–512.

The Principle of the Experiment. If a spring is not stretched beyond its elastic limit, it should obey Hooke's law, viz., the distance it is stretched is proportional to the stretching force. When stretched and then set free, the spring will move under the action of the force of restitution, which is opposite in direction to the displacement. If we denote the displacement by x and the force of restitution by F, we have

$$F = -cx, \tag{1}$$

where c is called the *force constant* of the spring. In text-books of physics it is shown that the motion of the spring is what is known as Simple Harmonic Motion, in which the acceleration is given by $a = -(4\pi^2/T^2)x$, where T = time required to make one complete vibration. But if the force is measured in absolute units (i.e., dynes or poundals), $F = ma$, whence

$$c = 4\pi^2 m/T^2, \tag{2}$$

m being the mass set in motion. In this case m is not merely the mass attached to the end of the spring but also the "equivalent mass of the spring." The equivalent mass of the spring should be about one half of its total mass.

Work to be Done. A. Determine the force constant of the spring of a spiral spring balance by suspending several different weights, ranging from, say, 2 gm. to 10 gm., from it and observing the corresponding elongations. Are the elongations proportional to the stretching forces? Determine the average value of c, using equation (1) and measuring the forces in grams weight and the elongations in centimeters.

B. Suspend a mass m_1 from the spring and determine the corresponding period of vibration T_1 by observing the time required to make 50 vibrations when the spring has been slightly stretched and set free. Include in m_1 the weight of the index and pan as well as standard weights in the pan. In this way make at least three concordant determinations of T_1. Using a second mass m_2 determine the corresponding T_2.

In both cases the spring is also set in motion but all parts of it

do not go through the whole motion of the mass suspended from it. Let the effectual mass of the spring be represented by m_s. Then $(m_1 + m_s)$ must be substituted for m in equation (2). Hence

$$(m_1 + m_s)/T_1^2 = (m_2 + m_s)/T_2^2.$$

Solve this equation for m_s and from the observed values of m_1, m_2, T_1, and T_2 calculate m_s. Using the value of m_s and either m_1 and T_1 or m_2 and T_2, calculate c.

C. Since the value of c calculated in part B is expressed in dynes per cm., and that calculated in part A is in grams weight per cm., unless some transformation unit has been used, it follows that the ratio of the value of c found in part B to that found in part A is the acceleration of gravity. Calculate the value of g, the acceleration of gravity, in this way. How does it compare with the accepted value of g in your locality? Is this method better than that used for determining g in Experiment 19? Give reasons for your answer.

52. THE ACCELERATION OF GRAVITY BY THE SIMPLE PENDULUM

Read Caswell's *An Outline of Physics*, pp. 512–515.

Preliminary Exercise. Attach a small steel ball to a fine thread and suspend it from a clamp with square jaws so that the center of the ball is 180 cm. from the point of support. Set it in vibration through an arc of about 10 cm. and find the time (to a fraction of a second if possible) of 50 complete vibrations, i.e., the time to go the length of the arc and back again. Make one trial each with the arc of the swing about 20 cm. and 30 cm., and also with the length of the arc about 200 cm. Compute the time of one vibration in each of the above. Does the period of vibration depend upon the length of the arc?

Suspend beside the first pendulum another of the same length but of different mass and material. Set the two swinging together and watch them for about a minute. Draw your conclusions regarding the effect of the amplitude and weight of the bob on the time of vibration.

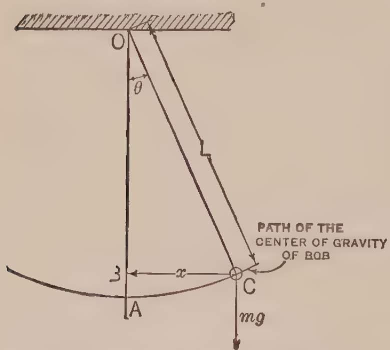


Fig. 21.—Simple Pendulum Torque Is Proportional to Angular Displacement.

Replace the last pendulum by a second with a bob like the first. Adjust until it makes exactly two swings to one of the first. Measure its length. What simple fractional part is this length of the first? Adjust again until it makes three swings to one of the long pendulum. Make the measurements and calculations as for the first adjustment. From these observations formulate a law relating the length of the pendulum to its period of vibration.

The Principle of the Experiment. A pendulum swinging through a small arc executes a simple harmonic motion of rotation and its period of vibration, T, may be found from the equation

$$G = -\frac{4\pi^2 \mathfrak{I} \theta}{T^2}, \tag{1}$$

where $\mathfrak{I}$ is the moment of inertia, θ is its angular displacement, and G is the torque acting upon it due to gravity. From Fig. 21 it appears that $G = -mg\theta L$, where m is its mass and L is the distance from its center of gravity to the point of support.

If it is a "simple pendulum," i.e., if its mass is practically concentrated in a massive ball at the lower end, $\mathfrak{I} = mL^2$, and we have

$$T = 2\pi\sqrt{\frac{L}{g}}, \tag{2}$$

or

$$g = \frac{4\pi^2 L}{T^2}. \tag{3}$$

Work to be Done. A. Suspend a metal sphere about 3 or 4 cm. in diameter from a rigid support by a fine wire about 0.05 cm. in diameter. The upper end of the wire may be attached to a light steel ring, such as a screw eye, and this should hang upon a suitable knife-edge. For convenience, the length of the pendulum should be about 99.5 cm. long. The length may be found by measuring from the knife-edge to the upper side of the ball, measuring the diameter of the ball with a vernier caliper and adding half of this quantity to the length previously obtained.

The period of the pendulum may be determined by observing the number of vibrations made by the pendulum in about half an hour. A pendulum of about the length indicated should require about two seconds to complete one vibration, or one second for each swing; so it will either gain or lose slowly compared with the pendulum of a large laboratory clock which beats seconds. One observer may watch the laboratory clock and count the seconds while a second observer watches the pendulum under test, noting when it coincides with the second's clock.

If the laboratory clock is connected to a time-circuit so that electric impulses are sent through the circuit once a second, these impulses may be used to operate a sounder and so dispense with the services of one observer.

An even better way is to have a fine wire project downward from the bob of the pendulum, so that it dips into a small mercury cup at the middle of the swing. A metal knife-edge is used and this and the mercury cup are connected to the time-circuit in series with the sounder. Whenever the wire attached to the bob is passing through the mercury cup at the instant when the electric impulse is sent through the circuit the sounder will operate. This is called *a coincidence*. The number of swings, i.e.,

half complete vibrations, of the pendulum under test for each coincidence is either one greater or one less than the number of seconds between coincidences. From these observations the period of the pendulum may be determined with a high degree of precision.

Determine the length of the pendulum as accurately as possible (to 0.01 cm. if possible) and the period by one of the methods outlined above, and calculate the value of the acceleration of gravity.

B. From the standard formula calculate the correct value of g for your altitude and latitude.

53. MOMENT OF INERTIA AND MODULUS OF RIGIDITY BY THE TORSION PENDULUM

Read Caswell's *An Outline of Physics*, pp. 506–507, 515–517.

The Principle of the Experiment. A torsion pendulum is constructed by suspending from the lower end of a long vertical wire, which is held in a chuck at the upper end, a flat circular disk. The wire is attached at the center of the disk and the plane of the disk is horizontal. The disk is rotated in the horizontal plane through a small angle and then set free. It vibrates with a simple harmonic motion of rotation. The period of the vibration is given by

$$T = 2\pi \sqrt{\frac{32\, L\mathfrak{J}}{\pi \rho d^4}}, \tag{1}$$

where L = length of the wire, d = its diameter, $\mathfrak{J}$ = moment of inertia of the disk and its attachments, and μ = coefficient or modulus of rigidity of the material of the wire.

Let a ring of uniform thickness, whose inner radius is R_1 and outer radius is R_2, and whose mass is M, be placed upon the disk, so that the axis of rotation of the disk passes through the center of the ring.

The moment of inertia of the ring alone is given by

$$\mathfrak{J}' = M\frac{R_1^2 + R_2^2}{2}, \tag{2}$$

and the moment of inertia of the loaded disk is $(\mathfrak{J} + \mathfrak{J}')$. From equation (1) it follows that

$$\mathfrak{J} = \frac{\mathfrak{J}'\, T^2}{(T'^2 - T^2)}, \tag{3}$$

where T = period of the disk alone, and T' = period of the disk with ring.

Work to be Done. A. Set the torsion pendulum to which you are assigned into vibration by turning the disk through an angle of 30 or 40 degrees and setting it free. Do this in such a manner that the pendulum is not set to swinging. Determine the time required to make, say, 50 complete vibrations, and calculate

T. Measure L to the nearest millimeter, and determine d by calipering the wire at a number of places with a micrometer caliper and taking the average value.

B. Weigh the heavy ring furnished you, and determine its inner and outer radii with a vernier caliper. Calculate $\mathcal{I}'$. Detach the bob of the pendulum from its support by loosening the chuck at either the upper or the lower end of the wire. Place the ring on the bob with the wire passing through the center of the ring, and suspend the bob as before. Determine the new period of vibration as in part A.

C. Using the values of $\mathcal{I}'$, T and T' which you have found, find the value of $\mathcal{I}$, the moment of inertia of the disk with its attachments alone.

D. Using the value of $\mathcal{I}$ found in part C and the other necessary data obtained in part A, with the aid of equation (1), calculate μ, the modulus of rigidity of the wire.

54. FREQUENCY OF A TUNING FORK AND SPEED OF SOUND

Read Caswell's *An Outline of Physics*, pp. 558–568.

The Principle of the Experiment. Determinations of the frequency of vibration of a tuning fork depend upon a comparison of the number of vibrations it makes in a given length of time with some other periodic occurrence whose frequency is known. Two methods are described below.

The speed of a wave-motion, such as sound, is related to its frequency, n, and its wave-length, λ, by the equation

$$v = n\lambda. \tag{1}$$

In the case of sound, the most convenient method of determining the wave-length is to set up standing waves in the medium and determine the distance between two successive nodes, this distance being half a wave-length.

Work to be Done. A. Determine the frequency of a fork by one of the following methods:

First Method. An electrically-maintained tuning-fork is so mounted that a stylus attached to one of its prongs is in contact with a sheet of smoked, or sensitized paper, upon a rotating drum. The axis of the drum is at right-angles to that of the fork, so that as the drum is rotated the stylus traces a wavy line on the surface of the paper. Another stylus, attached to the end of a spring which carries the armature of a small electromagnet, is mounted so as to trace a line close to that traced by the fork's stylus. The electromagnet is connected in the clock circuit so as to be magnetized once a second. Whenever it is magnetized, the stylus attached to the rod is suddenly jerked to one side, so that its trace is a straight line with a series of sharp kinks formed at intervals of one second.

Start the tuning-fork and close the time circuit through the electromagnet. Then rotate the drum slowly for several seconds. Count the number of waves traced by the fork during as many whole seconds as are shown on your paper, and determine the number of waves per second. This number is the frequency of the fork. Record your data and also include the sheet of paper attached to the drum in your report. If the paper is smoked, it should be covered with a thin coat of shellac to prevent smearing.

Second Method. The following is known as the stroboscopic method of determining frequency. The stroboscope is a large disk with a series of uniformly spaced radial slots near its periphery. It is mounted so that it can be rotated over an electrically-maintained tuning fork. The fork should be so placed that portions of both prongs can be seen through each of a number of these slots, the axis of the fork being perpendicular to the slots and the plane of the prongs of the fork being parallel to the plane of the disk. If the fork is set into vibration and the disk rotated at the same time, the prongs of the fork will not appear straight but will form a series of waves. Why is this? If the disk is rotated at such a speed that one slot passes before the eye for every vibration of the fork, these waves will appear fixed in position. Why? If it is rotated too rapidly, the waves will move in one direction and if too slowly in the opposite direction.

Rotate the disk at such a speed as to keep the waves as nearly stationary as possible, and from the number of rotations of the disk, determined with a speed counter, and the number of slots in the disk, determine the number of vibrations of the fork per second, i.e., the frequency. Care must be taken to be certain that the observed frequency is not a multiple or sub-multiple of the true frequency. Record any marks upon the fork.

B. A resonance tube is provided, which may be either a long vertical tube open at the upper end and in which the length of the air column can be varied by letting out or admitting water, or a tube in which the length of the air column can be varied by adjusting the position of a piston. Vibrate a fork of known frequency over the mouth of the tube and by varying the length of the air column find as many positions of maximum resonance as possible. A telephone receiver connected to an audio oscillator may be used instead of the fork. Determine the distance between two successive positions of maximum resonance as accurately as possible. The distance between two successive positions of resonance is one-half of the wave-length of the sound in air. From the average distance between successive positions of resonance and the frequency of the fork, determine the velocity of sound in air. Record the temperature during the experiment, and assuming that the velocity of sound increases 60.7 cm. per sec. per degree Centigrade rise in temperature, calculate the velocity of sound in air at 0° C. How does this calculated value agree with the commonly-accepted value?

C. A Kundt's tube consists of a long glass tube 3 or 4 cm. in diameter. Near one end of the tube is a closely-fitting plug

which can be moved to and fro by a handle passing through a suitable holder. The other end of the tube is provided with a clamp which holds a metal rod about a meter long at its center. The end of the rod projects into the tube and carries a disk which fits the tube loosely. Inside the tube between the plug and the disk a small amount of cork dust, or lycopodium powder, is placed. Rub the free end of the rod with rosined cloth or leather. The rod will vibrate longitudinally and emit a clear, shrill tone. A slow motion of the rubber with light pressure is most effective. If the disk on the end of the rod presses on the glass or if the rod is not clamped at its center, difficulty may be experienced in producing the tone. By adjusting the position of the plug the air column can be tuned in resonance with the tone emitted by the rod. When this adjustment is properly made the positions of the nodes and anti-nodes is clearly shown by the cork dust. The dust will be thrown into the air and fall in little piles. The points where the dust collects are the nodes. The positions of the nodes should be obtained as sharply as possible. Obtain the average distance between the nodes as accurately as possible. This will be a half wave-length of the sound in air, while the length of the rod will be a half wave-length in the solid. From the ratio of these two lengths and the velocity of sound in air at the temperature of the room, determine the velocity of the sound in the solid. Record the material of the solid and compare the value of the velocity of sound obtained by you with that given in tables.

55. LAWS OF VIBRATING STRINGS

Read Caswell's *An Outline of Physics*, pp. 564–566.

The Principle of the Experiment. From time immemorial it has been known that the tighter a string is stretched the higher will be the frequency of the musical note which it will emit when bowed or plucked. It has also been known that the shorter the string the higher the pitch will be. Standing waves are set up in the string and if the string is vibrating in its simplest, or fundamental, node, the two ends of the string will be nodes and the length of the string will be half a wave-length.

Moreover, the speed of the waves in the string is given by

$$v = \sqrt{\text{Tension/Mass of the string per unit length.}} \qquad (1)$$

Combining these two relations we find that

$$n = \frac{1}{Ld}\sqrt{F/\pi D}, \qquad (2)$$

where n = frequency, L = length of the string, d = diameter of the string, F = tension in dynes, D = density, using c.g.s. units throughout.

Work to be Done. A. Procure two steel wires, one having about twice the diameter of the other. Numbers 20 and 26, B. and S. wire gauge (about 0.8 mm. and 0.4 mm.) will do. Also procure an aluminum wire, or a wire of some other metal of low density, such as duraluminum, having approximately the same diameter as the larger steel wire. Stretch the smaller of the two steel wires on a sonometer and adjust its length until it is in unison with the lower of two tuning forks, of known frequency, using a known force of 5 to 10 kilograms weight. If one has not a good ear for sound pitch the adjustment can be made quite accurately by sounding the wire and fork alternately, noticing which is the higher, until the adjustment is close enough for the production of beats when sounded simultaneously. Then sound them simultaneously and adjust the length of the wire so as to make the beats farther and farther apart until they finally disappear. Record this length. Repeat with the higher fork. Show that the frequency is inversely proportional to the length.

B. Stretch the second steel wire on the sonometer using the

same stretching force as for the first and adjust its length until the two are in unison. From the result of the preceding section determine the frequency it would have if its length were the same as that of the first wire. Measure the diameters of the wires. Show that for wires of the same material and the same length the frequency is inversely proportional to their diameters.

C. Change the tension on the second wire and adjust its length until it is in unison with the first. From its new length and the length it had when adjusted in the preceding paragraph determine what its frequency would have been with the new stretching force but the original length. Show that this result leads to the conclusion that the frequency is directly proportional to the square root of the stretching force, the length being kept constant.

D. Replace the smaller steel wire by the wire of low density and approximately the same diameter as the larger steel wire. Stretch both with the same force. If aluminum is used, the ratio of the stretching force to the cross-section of the wire should not exceed 6 kg./mm.^{2} Adjust their lengths until they have the same pitch. Any convenient pitch will do. Assuming that the frequency of a stretched wire is inversely proportional to the square root of its density and that the density of steel is 7.8 gm./cc., compute the density of the other wire from the lengths of the two wires. Compare this density with that given in the tables.

E. Calculate the frequencies of the two forks used in part A from equation (2). How do these values agree with the known frequencies of the forks?

56. VIBRATIONS OF ELASTIC BODIES

Read Caswell's *An Outline of Physics*, pp. 564–568.

The Principle of the Experiment. Elastic bodies when set into vibration tend to produce standing waves. Nodes are produced wherever the material is held so as to prevent motion. If two nodes are produced in this way, other nodes may occur which are symmetrically situated with respect to these. Midway between nodes antinodes are produced. Thus a string fastened at the two ends and "damped" at the middle by being touched with the finger will vibrate in two loops, the nodes being at the two ends and the middle; but if "damped" one-third of its length from one end, it will vibrate in three loops, one of the nodes occurring where it is not damped. Or if "damped" one-fourth of its length from one end it will vibrate in four loops, with two free nodes.

If a circular plate is fastened at its center and set into vibration by bowing, radial nodes may be set up extending from the center to the edge. There may be any number of these nodes and between every adjacent pair of nodes there is an antinode. There may also be a number of nodes in the form of concentric circles, the center of the disk being a node and the circumference an antinode. The form and arrangement of nodes and antinodes depends upon the shape of the vibrating object, how it is fastened, how damped, and how the vibrations are excited. In the following paragraphs the student is given suggestive instructions for setting up vibrations in strings and plates.

Work to be Done. A. Stretch a wire on a vertical sonometer by hanging a pail from its lower end and adjust the tension by pouring water into or out of the pail. Using a fork of low frequency, adjust the tension until the wire has the same pitch as the fork. The clamp should hold the wire so as to prevent vibrations of the wire in the clamp, but not support the weight. The "length" of the wire is the distance between the clamps. Adjustment for pitch may be made by sounding the fork and wire alternately (the sound of the fork being enhanced by holding the butt against the sonometer) and noticing which is the higher in pitch. In this way the adjustment can be made close enough to produce beats. Then by careful adjustment the beats can be made to occur further and further apart until the two are in unison. Without changing the tension on the wire, place a

bridge at its center. Then find a fork having the same pitch as either half of the wire. State any obvious relation which exists between the length of the wire and its frequency of vibration. The experiment may be repeated, dividing the wire into other fractions of its length, such as one-third or two-thirds. Notice the difference in pitch of the two segments of the wire.

B. Remove the bridge and pour water into the pail until the pitch of the wire is the same as that of a fork an octave higher than the original one, noting the weight of water and pail both before and after this change. Note the ratio of the two frequencies of the forks and also the ratio of the two tensions. Do you observe any relation between these ratios? If so, what is it?

C. Clamp a rod at its middle point and stroke with a resin-coated cloth or piece of leather. Note the pitch of the rod. Repeat, using a rod of different length. How does the pitch of the rod change with its length? Clamp one of the rods a little less than one-fourth of its length from one end and stroke the shorter end. See if you can make it vibrate so as to give a note of higher pitch than that originally obtained. If so, how do you account for it?

D. Clamp a Chladni's plate firmly at its center and sprinkle sand on it. Then touch a point on the edge with your finger and bow the plate at a number of points and see whether you can obtain a number of symmetrical patterns formed by the sand. By reference to a text one may get suggestions as to possible patterns. See whether you can account for these patterns. If you had a circular plate and pressed it out in the center to form a bell, would you expect it to emit a single tone or a combination of tones? What characteristic of sound is illustrated by this combination?

E. An electrically-maintained tuning-fork is mounted with its axis horizontal. A stout string, such as a piece of fish line is attached to one prong of the fork and is stretched in the direction of the axis of the fork, passes over a light pulley and has a weight attached to the end. By varying the weight attached to the end see whether you can cause the string to vibrate in one, two, three of more, loops, and note the weight for each set of loops. Tabulate your results. Draw conclusions.

57A. WAVE-LENGTH OF LIGHT BY SIMPLE METHOD

Read Caswell's *An Outline of Physics*, pp. 602–606.

The Principle of the Experiment. In text-books of physics it is shown that if monochromatic light from a line source, such as an illuminated slit, passes through a diffraction grating, in which the distance between any two adjacent lines of the grating = c, and falls upon a screen at a distance D from the grating, a series of images of the slit will appear upon the screen. See Fig. 22. One of these images, called the "central image," is in line with the source and the center of the diffraction grating. The images on either side of it are called "diffracted images" and are numbered from the central image. If d = distance from the central to the nth diffracted image, and λ = wave-length of the light,

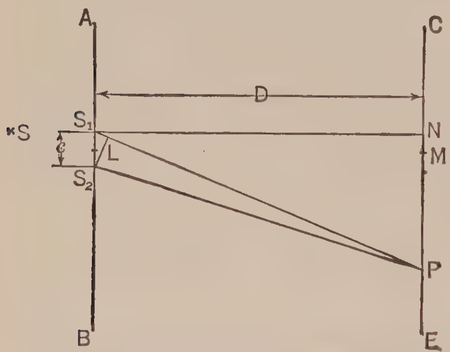


Fig. 22.—Measurement of the Wave-Length of Light.

$$\lambda = cd/nD. \tag{1}$$

A brass screen is provided which has one slit on one side and a pair of slits on the opposite side of a central vertical line. See right of Fig. 23. The screen is clamped with its plane vertical and the slits horizontal. A Bunsen burner giving a strong yellow sodium flame is placed in front of it. A diffraction grating is mounted on a movable slider on a meter stick, with the ruled lines parallel to the slits in the screen. The stick is supported by clamps so that the grating may be moved along a line perpendicular to the screen as shown in Fig. 23. One slit of the pair is covered, so that one slit is open on each side of the central line. On looking at the slits through the grating a series of diffracted images of the slits will be seen. If the grating is moved back and forth, a position of the grating may be found such that one of the diffracted images in the one set seems to form a continuous

line with the central, or principal, image in the other set. Let this be the nth diffracted image, let d' = distance between the slits in the brass screen, and let D' = distance from the screen

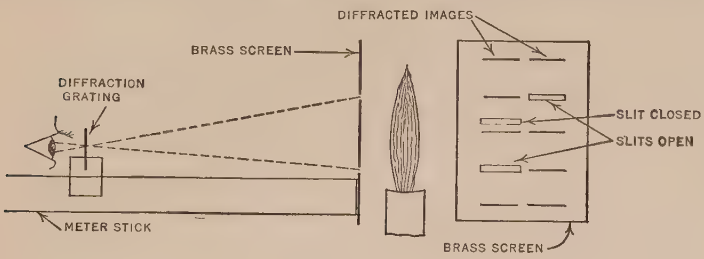


FIG. 23.

to the diffraction grating. The student should be able to show that

$$\frac{d'}{D'} = \frac{d}{D}. \tag{2}$$

Combining equations (1) and (2) we have

$$\lambda = cd'/nD'.$$

Work to be Done. A. Using that slit of the pair which is nearest to the single slit, find as many positions of the grating for which coincidence of the images as outlined above may be obtained as is conveniently possible. Record the values of n and D' in each case and calculate the products nD'. Measure the distance d' with a micrometer caliper, and calculate λ, using the average value of the products nD'. The value of c is usually marked on the grating. If in doubt about its value ask the instructor.

B. Repeat A, using the other slit of the pair.

C. How closely do your values of the wave-length agree? What is its true value? How closely does your average result agree with this?

57B. WAVE-LENGTH OF LIGHT BY GRATING SPECTROMETER

Read Caswell's *An Outline of Physics*, pp. 602–608.

The Principle of the Experiment. Where a high degree of accuracy is required or where the light is composed of several different colors, or wave-lengths, the method used for determining the wave-length in the preceding experiment is worthless. For high-class measurements of wave-length a spectrometer equipped with a diffraction grating having 6,000 to 10,000 lines to the centimeter is used.

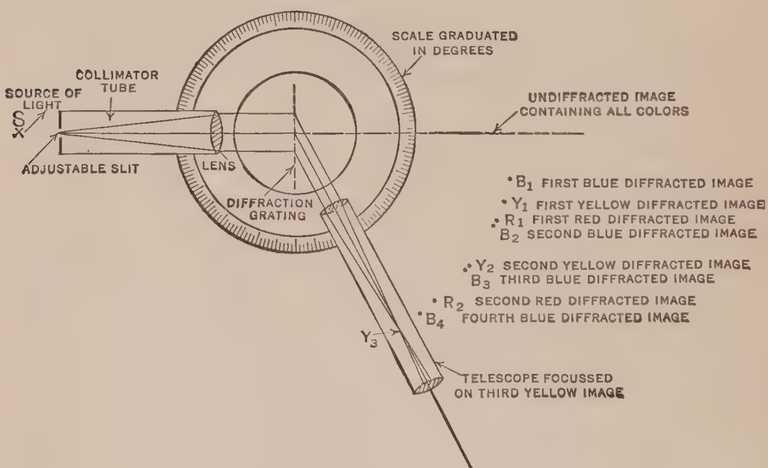


FIG. 24.—Diffraction-Grating Spectrometer.

The essential parts of a spectrometer are the collimator, the table, the telescope and the graduated scale. (See Fig. 24.) The collimator consists of a tube with an adjustable slit at one end and a convex lens at the other, the slit being at the principal focus of the lens, so that light diverging from the slit and passing through the lens emerges as a beam with a plane wave-front. The diffraction grating is placed in a vertical position on the table so that the lines on it are parallel to the slit. If light entering the slit has wave-lengths λ_1, λ_2, λ_3, etc., beams of light will emerge from the diffraction grating with different directions for each different wave-length. There will be a bright central image

formed in the telescope which has the same position as if no diffraction grating were present. If the telescope is rotated around the table so as to bring the light in each of the beams to a focus, it will be found that for each separate value of λ there is a series of angles similarly situated with reference to the central image on either side of it, where images of the slit are formed. If the angles between the central image and the images to the right of it, say, are named in order, θ_1, θ_2, etc., and if the distance between two lines of the grating, i.e., the grating constant, is denoted by c,

$$\lambda = c \sin \theta_1, \qquad 2\lambda = c \sin \theta_2, \qquad 3\lambda = c \sin \theta_3, \qquad \text{etc.} \qquad (1)$$

Work to be Done. A. Mount a diffraction grating on the table of the spectrometer so that its plane is vertical and perpendicular to the axis of the collimator. Place a source of light, e.g., a Bunsen burner with an attachment to produce a yellow sodium flame, in front of the slit and rotate the telescope until its axis is coincident with that of the collimator. Adjust the eyepiece of the telescope until the cross-hairs are sharply focussed. In doing this it is well to have the slit fairly wide. The width of the slit is regulated by turning the screw attached to the slit. After focussing the telescope the width of the slit may be reduced until it is as narrow as possible without cutting off too much light.

Place the telescope so that the cross-hairs are close to the slit and then clamp the telescope. Using the fine adjustment, slowly move the telescope until the cross-hairs are seen at the center of the image of the slit. Choosing a particular line in the spectrum find the positions of the telescope for θ_1, θ_2, etc., both to the right and the left of the central image. Calculate the values of λ from your different readings and take the average.

B. Repeat for lines in the spectra of a number of other salts, e.g., lithium chloride, strontium chloride, and calcium chloride. Tabulate your results, showing the chemical used, the wave-length observed, and the true wave-length as given in standard tables.

58. DOUBLE REFRACTION AND POLARIZATION

Read Caswell's *An Outline of Physics*, pp. 623–638.

The Principle of the Experiment. Light consists of transverse electromagnetic waves in the luminiferous ether. That is, when light passes through a point in space electric stresses are set up at the point which may vary in magnitude and direction but the direction of the stress always lies in a plane perpendicular to the direction of propagation of the light. Simultaneously with the production of these electric stresses magnetic stresses are set up which are perpendicular both to the electric stresses and to the direction of propagation of the light. Light in which the electric stresses always have a certain direction, or the opposite direction, is said to be plane-polarized. Such light may be thought of as due to the motion of an electron in the source of light moving in such a way that to an observer at the point where the light is being studied it seems to be moving to and fro in a straight line. If its apparent path is a circle, the light is said to be circularly-polarized, and if its apparent path is an ellipse, the light is said to be elliptically polarized. The light from a source may therefore appear to be circularly-polarized when the source is seen from one direction and plane-polarized when seen from a direction at right-angles to the first.

Due to differences in the elastic properties of crystals in different directions the speed of light in a crystal may be different in different directions, and these differences cause a light wave passing through a crystal to break up into two waves, the directions of the electric vibrations in the two waves being at right-angles to each other. In this experiment we become acquainted with some of the phenomena of polarization and double refraction.

Work to be Done. A. If a pinhole in a card is held to the light and looked at through a calcite crystal there may seem to be two pinholes instead of one. If a polished section of calcite is laid on a printed page, two images of the letters may be seen through the crystal. Observe the above phenomena. The calcite crystal is very soft and easily scratched and should be handled carefully. Describe what happens when the crystal is rotated about an axis perpendicular to the plane of the paper. How many refractive indices has calcite? See if you can find a direc-

tion in which light passes through the crystal forming only one image. This direction is called the ***optic axis*** of the crystal. How many refractive indices has calcite in the direction of the optic axis? One refractive index of calcite is the same in all directions. The wave, or ray, for which this is true is called the ***ordinary ray***. What is the shape of the wave-front of the ordinary ray? The ray for which the refractive index varies in different directions is called the ***extraordinary ray***. In what direction is the refractive index the same for both rays? The refractive index for the ordinary ray in calcite is 1.66, that for the extraordinary ray in a direction at right-angles to the optic axis is 1.49. Which wave-front is outside the other? Will the two wave-fronts coincide anywhere? What is the shape of the extraordinary wave-front in calcite? Is the difference in refractive index due to a difference in vibration frequency of the two waves? Give reasons for your answers. In quartz the refractive index for the ordinary ray is 1.54 and for the extraordinary ray is 1.55. Which wave-front is outside the other in this case? What is the shape of the extraordinary wave-front in quartz?

B. *Light Waves Transverse or Longitudinal?* Tourmaline is also a doubly refracting crystal but the ordinary ray is rapidly absorbed, so that a piece of tourmaline more than a millimeter thick only transmits the extraordinary ray. Hold one of the tourmaline plates of the tourmaline tongs between the eye and the calcite crystal and observe the two images as before while the tourmaline plate is rotated about the ray of light as an axis. Observe that in certain positions of the tournaline one image disappears and when the tourmaline has been rotated through a right-angle from this position the other image disappears and the first re-appears. Since tourmaline allows only its extraordinary ray to pass, one of the calcite rays must be the extraordinary ray of the tourmaline in one position, while in a position at right-angles to this the other calcite ray becomes the extraordinary tourmaline ray. Place the two tourmaline plates together and rotate one of them. Record your observations in each of the above cases. Can you explain these results by assuming that the vibrations in the light wave in each ray are all in one direction perpendicular to the direction of the rays (i.e., transverse waves). If so, is there any relation between the directions of the vibrations in the two rays? What is the relation? Could the above results be explained by assuming the vibrations to be taking place in the direction of propagation of the light as is the case in sound, i.e.,

that light waves are longitudinal? Can longitudinal waves be polarized?

C. *Production of Polarized Light by a Nicol Prism.* A Nicol prism consists of two pieces of calcite cemented together with Canada balsam, the refractive index of which is 1.55. What is the refractive index of the ordinary ray in calcite with respect to Canada balsam, instead of air, as a standard? What is the critical angle for the ordinary ray in calcite passing into Canada balsam? What will happen if the light is incident at a greater angle? Does this furnish a means of polarizing light? Explain. Pass light which has already passed through a tourmaline plate or has been reflected from a black glass plate at an angle of about 55 or 60 degrees through a Nicol prism and rotate the prism about the line of sight as an axis, and observe the results. Does the Nicol seem to affect the light in a manner similar to the tourmaline? What does this indicate?

D. *Production of Polarized Light by Reflection.* The polariscope has a black glass plate at its lower end which reflects light up the tube of the polariscope so as to pass through a Nicol prism or be reflected at another glass plate, either of which can be rotated about the axis of the tube. Place the polariscope so that light from a window falls directly upon the black glass plate (called the polarizer) and rotate the Nicol, or second glass plate (called the analyser). Record your observations. Is reflected light polarized? Assuming that the polariscope is so constructed that when the beam of light is reflected parallel to the axis of the tube a maximum amount of light is polarized, from the dimensions of the instrument find the tangent of the angle of incidence corresponding to maximum polarization. Is there any relation between the tangent of this angle, called the angle of polarization, and the refractive index of the polarizing glass plate? If so, what?

E. *Production of Polarized Light by Transmission.* Substitute a pile of thin glass plates for the analyser previously used, and see if you can find any evidence that the pile of plates polarizes the transmitted light. Hold the pile so that the angle of incidence has various values between say, 30° and 60°.

F. *Examples of Polarization.* You are provided with pieces of mica of various thicknesses cemented onto pieces of glass, also pieces of unannealed glass and various crystals. Place one of these between the analyser and polarizer of the polariscope and rotate the former. Then rotate the specimen. Record your observations. Repeat for each specimen.

Place a piece of annealed glass in a metal clamp and tighten the clamp so as to set up mechanical stresses in the glass, and examine the glass in the polariscope.

59A. MAGNETIC PERMEABILITY

Read Caswell's *An Outline of Physics*, pp. 278–290, 647–653.

Preliminary Experiment. Connect a coil of wire containing about 200 turns of copper wire in series with a lamp-bank and the 110-volt D.C. mains, and turn in a sufficient number of lamps so as to have a current of 2 or 3 amperes through the coil. Place a rod of some metal such as copper inside the coil with its end protruding and test its ability to pick up objects such as wire nails, brass tacks, pieces of glass, wood, etc. Remove the rod from the coil and again test for this property. Repeat with a number of rods of other metals, including soft iron and hard steel. What differences do you observe, both as to the immediate and after effects?

The Principle of the Experiment. Whenever there is an electric current in a wire the region surrounding the wire is a magnetic field. Each point in the field is characterized by a quantity known as the magnetizing force, or magnetic intensity, of the field at that point if the space is filled with air. If the space is filled with some other material, each point is characterized by a corresponding quantity known as the magnetic induction at that point. The ratio of the magnetic induction to the magnetizing force is called the magnetic permeability. Expressed mathematically $\mu = B/H$, where μ = permeability, B = magnetic induction, and H = magnetizing force.

The traction permeameter used in this experiment consists of a heavy rectangular iron "yoke" with a small magnetizing coil in an opening at its center. The specimen to be tested consists of a long rod of uniform circular cross-section. This is slipped through a snugly-fitting opening in the yoke, through the coil and against the opposite side of the yoke. The end of the rod and the yoke are machined so as to provide as good a contact as possible. A current is then started in the coil and the rod is pulled away from the yoke with the aid of a lever.

The force F (in dynes) required to pull the rod loose is related to B by the following equation.

$$B = \sqrt{\frac{8\pi F}{A}} \tag{1}$$

where A is the cross-sectional area of the rod. The flux through the magnetic circuit is given by

$$\phi = BA. \tag{2}$$

The magnetomotive force due to the current in the coil is

$$\mathcal{F} = 4\pi NI/10, \tag{3}$$

where N is the number of turns and I is the current in the coil. Also

$$\mathcal{F} = \phi\mathcal{R} \tag{4}$$

where $\mathcal{R}$ is the reluctance of the entire magnetic circuit, including both rod and yoke. Combining equations (1), (2), (3), and (4), we obtain

$$\mathcal{R} = \frac{4\pi NI}{10} \cdot \frac{1}{\sqrt{8\pi FA}}. \tag{5}$$

But

$$\mathcal{R} = \frac{L_1}{\mu_1 A_1} + \frac{L_2}{\mu_2 A_2} \tag{6}$$

In equation (6) A_1 stands for the cross-section of the rod and A_2 for that of the yoke, L_1 for the length of the rod exposed in the yoke, being the length of the magnetic circuit through the rod, and L_2 is the estimated average length of the magnetic circuit through the yoke. μ_1 and μ_2 are the corresponding permeabilities.

Work to be Done. A. Determine the cross-section of the rod, the length of the opening in the yoke, and the number of turns of wire in the coil. Also estimate the average cross-section of the magnetic circuit in the yoke and its length. Record the number or material of the specimen.

Connect the coil in series with a lamp rheostat, an ammeter, and the 110-volt D.C. mains. The specimen should be first demagnetized. This can be done by taking the coil from the permeameter yoke and inserting the specimen first in one end of the coil, then in the other, gradually reducing the current. It can also be demagnetized in the frame by using a reversing switch or alternating current. Do NOT demagnetize by hammering the specimen. Place specimen and coil in position. Turn in the smallest lamp in the rheostat, observing the current, and determine the force F necessary to detach the rod. Be sure to have the contact between the end of the specimen and the yoke clean and smooth. A slight twist of the specimen after the current

has been adjusted will improve the contact. Make a series of observations by turning in the smallest lamp in the rheostat first and thereafter increase currents by as small steps as possible until a current of about one ampere is reached. After that use any convenient currents until a current of about five amperes is reached. In each case the average of several trials should be taken to eliminate contact and other errors.

From equation (1) calculate the values of B and from equation (5) the corresponding values of $\mathcal{R}$. N.B. A great deal of time will be saved in making the computations by calculating the factor which is common to all these values in each equation. Thus $B = c\sqrt{F}$, and $\mathcal{R} = c'I/\sqrt{F}$. c and c' should be calculated once only. It will be found advisable to use a slide rule in these computations. Having found $\mathcal{R}$, calculate μ_1 from equation (6), assuming that $\mu_1 = \mu_2$. From the values of B and μ calculate the corresponding values of H.

B. Plot one curve using values of B as ordinates and H as abscissæ, and a second curve using values of μ as ordinates and H as abscissæ.

C. Repeat parts A and B for a second specimen.

59B. MAGNETIC PERMEABILITY—SIMPLIFIED CALCULATION

This experiment is identical with Experiment 59A except in the mode of computation of H and μ. Treating the rod and coil as if they were a long straight solenoid with a metal core,

$$H = 4\pi n I/10, \tag{7}$$

where n is the number of turns of wire per centimeter length of the solenoid. We cannot regard the length of the opening in the yoke as the length of the solenoid, but we may obtain an approximate result by making a suitable allowance for the remainder of the magnetic circuit. Nothing is to be gained in this method if the student must estimate the proper allowance to be made for the yoke, but the instructor may make this estimate and give the value to the student.

In a form of the traction permeameter which is in common use the reluctance of the yoke is approximately equal to about 0.7 cm. length of the rod. If N is the number of turns of wire in the coil and L the length of the opening in the yoke,

$$n = N/(L + 0.7).$$

Substituting this value of n in equation (7) we may find H, and from the value of B, found by using equation (1), Experiment 59A, μ may be calculated.

APPENDIX

NATURAL TRIGONOMETRIC FUNCTIONS

Rad	Deg	Tan	Sin	Log Sin	Log Cos	Cos	Cot		
0000	0	0000	0000	$-\infty$	0	1	∞	90	$\pi/2$
0175	1	0175	0175	2419	9999	9998	57.29	89	1.553
0349	2	0349	0349	5428	9997	9994	28.64	88	1.536
0524	3	0524	0523	7188	9994	9986	19.08	87	1.518
0698	4	0699	0698	8436	9989	9976	14.30	86	1.501
0873	5	0875	0872	9403	9983	9962	11.43	85	1.484
1047	6	1051	1045	0192	9976	9945	9.514	84	1.466
1222	7	1228	1219	0859	9968	9925	8.144	83	1.449
1396	8	1405	1392	1436	9958	9903	7.115	82	1.431
1571	9	1584	1564	1943	9946	9877	6.314	81	1.414
1745	10	1763	1736	2397	9934	9848	5.671	80	1.396
1920	11	1944	1908	2806	9919	9816	5.145	79	1.379
2094	12	2126	2079	3179	9904	9781	4.705	78	1.361
2269	13	2309	2250	3521	9887	9744	4.331	77	1.344
2443	14	2493	2419	3837	9869	9703	4.011	76	1.326
2618	15	2679	2588	4130	9849	9659	3.732	75	1.309
2793	16	2867	2756	4403	9828	9613	3.487	74	1.292
2967	17	3057	2924	4659	9806	9563	3.271	73	1.274
3142	18	3249	3090	4900	9782	9511	3.078	72	1.257
3316	19	3443	3256	5126	9757	9455	2.904	71	1.239
3491	20	3640	3420	5341	9730	9397	2.747	70	1.222
3665	21	3839	3584	5543	9702	9336	2.605	69	1.204
3840	22	4040	3746	5736	9672	9272	2.475	68	1.187
4014	23	4245	3907	5919	9640	9205	2.356	67	1.169
4189	24	4452	4067	6093	9607	9135	2.246	66	1.152
4363	25	4663	4226	6259	9573	9063	2.145	65	1.134
4538	26	4877	4384	6418	9537	8988	2.050	64	1.117
4712	27	5095	4540	6570	9499	8910	1.963	63	1.100
4887	28	5317	4695	6716	9459	8829	1.881	62	1.082
5061	29	5543	4848	6856	9418	8746	1.804	61	1.065
5236	30	5774	5000	6990	9375	8660	1.732	60	1.047
5411	31	6009	5150	7118	9331	8572	1.664	59	1.030
5585	32	6249	5299	7242	9284	8480	1.600	58	1.012
5760	33	6494	5446	7361	9236	8387	1.540	57	9948
5934	34	6745	5592	7476	9186	8290	1.483	56	9774
6109	35	7002	5736	7586	9134	8192	1.428	55	9599
6283	36	7265	5878	7692	9080	8090	1.376	54	9425
6458	37	7536	6018	7795	9023	7986	1.327	53	9250
6632	38	7813	6157	7893	8965	7880	1.280	52	9076
6807	39	8098	6293	7989	8905	7771	1.235	51	8901
6981	40	8391	6428	8081	8843	7660	1.192	50	8727
7156	41	8693	6561	8169	8778	7547	1.150	49	8552
7330	42	9004	6691	8255	8711	7431	1.111	48	8378
7505	43	9325	6820	8338	8641	7314	1.072	47	8203
7679	44	9657	6947	8418	8569	7193	1.036	46	8029
7854	45	1	7071	8495	8495	7071	1.000	45	7854
		Cot	Cos	Log Cos	Log Sin	Sin	Tan	Deg	Rad

FOUR PLACE LOGARITHMS

N	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
10	0000	0043	0086	0128	0170	0212	0253	.0294	0334	0374	4	8	12	17	21	25	29	33	37
11	0414	0453	0492	0531	0569	0607	0645	0682	0719	0755	4	8	11	15	19	23	26	30	34
12	0792	0828	0864	0899	0934	0969	1004	1038	1072	1106	3	7	10	14	17	21	24	28	31
13	1139	1173	1206	1239	1271	1303	1335	1367	1399	1430	3	6	10	13	16	19	23	26	29
14	1461	1492	1523	1553	1584	1614	1644	1673	1703	1732	3	6	9	12	15	18	21	24	27
15	1761	1790	1818	1847	1875	1903	1931	1959	1987	2014	3	6	8	11	14	17	20	22	25
16	2041	2068	2095	2122	2148	2175	2201	2227	2253	2279	3	5	8	11	13	16	18	21	24
17	2304	2330	2355	2380	2405	2430	2455	2480	2504	2529	2	5	7	10	12	15	17	20	22
18	2553	2577	2601	2625	2648	2672	2695	2718	2742	2765	2	5	7	9	12	14	16	19	21
19	2788	2810	2833	2856	2878	2900	2923	2945	2967	2989	2	4	7	9	11	13	16	18	20
20	3010	3032	3054	3075	3096	3118	3139	3160	3181	3201	2	4	6	8	11	13	15	17	19
21	3222	3243	3263	3284	3304	3324	3345	3365	3385	3404	2	4	6	8	10	12	14	16	18
22	3424	3444	3464	3483	3502	3522	3541	3560	3579	3598	2	4	6	8	10	12	14	16	17
23	3617	3636	3655	3674	3692	3711	3729	3747	3766	3784	2	4	6	7	9	11	13	15	17
24	3802	3820	3838	3856	3874	3892	3909	3927	3945	3962	2	4	5	7	9	11	12	14	16
25	3979	3997	4014	4031	4048	4065	4082	4099	4116	4133	2	4	5	7	9	10	12	14	16
26	4150	4166	4183	4200	4216	4232	4249	4265	4281	4298	2	3	5	7	8	10	11	13	15
27	4314	4330	4346	4362	4378	4393	4409	4425	4440	4456	2	3	5	6	8	9	11	12	14
28	4472	4487	4502	4518	4533	4548	4564	4579	4594	4609	2	3	5	6	8	9	11	12	14
29	4624	4639	4654	4669	4683	4698	4713	4728	4742	4757	1	3	4	6	7	9	10	12	13
30	4771	4786	4800	4814	4829	4843	4857	4871	4886	4900	1	3	4	6	7	9	10	11	13
31	4914	4928	4942	4955	4969	4983	4997	5011	5024	5038	1	3	4	5	7	8	10	11	12
32	5051	5065	5079	5092	5105	5119	5132	5145	5159	5172	1	3	4	5	7	8	9	11	12
33	5185	5198	5211	5224	5237	5250	5263	5276	5289	5302	1	3	4	5	7	8	9	11	12
34	5315	5328	5340	5353	5366	5378	5391	5403	5416	5428	1	2	4	5	6	8	9	10	11
35	5441	5453	5465	5478	5490	5502	5514	5527	5539	5551	1	2	4	5	6	7	9	10	11
36	5563	5575	5587	5599	5611	5623	5635	5647	5658	5670	1	2	4	5	6	7	8	10	11
37	5682	5694	5705	5717	5729	5740	5752	5763	5775	5786	1	2	4	5	6	7	8	9	11
38	5798	5809	5821	5832	5843	5855	5866	5877	5888	5899	1	2	3	5	6	7	8	9	10
39	5911	5922	5933	5944	5955	5966	5977	5988	5999	6010	1	2	3	4	5	7	8	9	10
40	6021	6031	6042	6053	6064	6075	6085	6096	6107	6117	1	2	3	4	5	6	8	9	10
41	6128	6138	6149	6160	6170	6180	6191	6201	6212	6222	1	2	3	4	5	6	7	8	9
42	6232	6243	6253	6263	6274	6284	6294	6304	6314	6325	1	2	3	4	5	6	7	8	9
43	6335	6345	6355	6365	6375	6385	6395	6405	6415	6425	1	2	3	4	5	6	7	8	9
44	6435	6444	6454	6464	6474	6484	6493	6503	6513	6522	1	2	3	4	5	6	7	8	9
45	6532	6542	6551	6561	6571	6580	6590	6599	6609	6618	1	2	3	4	5	6	7	8	9
46	6628	6637	6646	6656	6665	6675	6684	6693	6702	6712	1	2	3	4	5	6	7	7	8
47	6721	6730	6739	6749	6758	6767	6776	6785	6794	6803	1	2	3	4	5	6	7	7	8
48	6812	6821	6830	6839	6848	6857	6866	6875	6884	6893	1	2	3	4	5	6	7	7	8
49	6902	6911	6920	6928	6937	6946	6955	6964	6972	6981	1	2	3	4	4	5	6	7	8
50	6990	6998	7007	7016	7024	7033	7042	7050	7059	7067	1	2	3	3	4	5	6	7	8
51	7076	7084	7093	7101	7110	7118	7126	7135	7143	7152	1	2	3	3	4	5	6	7	8
52	7160	7168	7177	7185	7193	7202	7210	7218	7226	7235	1	2	3	3	4	5	6	7	7
53	7243	7251	7259	7267	7275	7284	7292	7300	7308	7316	1	2	2	3	4	5	6	6	7
54	7324	7332	7340	7348	7356	7364	7372	7380	7388	7396	1	2	2	3	4	5	6	6	7
N	0	1	2	3	4	5	6	7	8	9	1	2	2	4	5	6	7	8	9

The proportional parts are stated in full for every tenth at the right-hand side. The logarithm of any number of four significant figures can be read directly by add-

N	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
55	7404	7412	7419	7427	7435	7443	7451	7459	7466	7474	1	2	2	3	4	5	5	6	7
56	7482	7490	7497	7505	7513	7520	7528	7536	7543	7551	1	2	2	3	4	5	5	6	7
57	7559	7566	7574	7582	7589	7597	7604	7612	7619	7627	1	1	2	3	4	5	5	6	7
58	7634	7642	7649	7657	7664	7672	7679	7686	7694	7701	1	1	2	3	4	4	5	6	7
59	7709	7716	7723	7731	7738	7745	7752	7760	7767	7774	1	1	2	3	4	4	5	6	7
60	7782	7789	7796	7803	7810	7818	7825	7832	7839	7846	1	1	2	3	4	4	5	6	6
61	7853	7860	7868	7875	7882	7889	7896	7903	7910	7917	1	1	2	3	3	4	5	6	6
62	7924	7931	7938	7945	7952	7959	7966	7973	7980	7987	1	1	2	3	3	4	5	5	6
63	7993	8000	8007	8014	8021	8028	8035	8041	8048	8055	1	1	2	3	3	4	5	5	6
64	8062	8069	8075	8082	8089	8096	8102	8109	8116	8122	1	1	2	3	3	4	5	5	6
65	8129	8136	8142	8149	8156	8162	8169	8176	8182	8189	1	1	2	3	3	4	5	5	6
66	8195	8202	8209	8215	8222	8228	8235	8241	8248	8254	1	1	2	3	3	4	5	5	6
67	8261	8267	8274	8280	8287	8293	8299	8306	8312	8319	1	1	2	3	3	4	5	5	6
68	8325	8331	8338	8344	8351	8357	8363	8370	8376	8382	1	1	2	3	3	4	4	5	6
69	8388	8395	8401	8407	8414	8420	8426	8432	8439	8445	1	1	2	3	3	4	4	5	6
70	8451	8457	8463	8470	8476	8482	8488	8494	8500	8506	1	1	2	3	3	4	4	5	6
71	8513	8519	8525	8531	8537	8543	8549	8555	8561	8567	1	1	2	3	3	4	4	5	6
72	8573	8579	8585	8591	8597	8603	8609	8615	8621	8627	1	1	2	3	3	4	4	5	6
73	8633	8639	8645	8651	8657	8663	8669	8675	8681	8686	1	1	2	2	3	4	4	5	5
74	8692	8698	8704	8710	8716	8722	8727	8733	8739	8745	1	1	2	2	3	4	4	5	5
75	8751	8756	8762	8768	8774	8779	8785	8791	8797	8802	1	1	2	2	3	3	4	5	5
76	8808	8814	8820	8825	8831	8837	8842	8848	8854	8859	1	1	2	2	3	3	4	4	5
77	8865	8871	8876	8882	8887	8893	8899	8904	8910	8915	1	1	2	2	3	3	4	4	5
78	8921	8927	8932	8938	8943	8949	8954	8960	8965	8971	1	1	2	2	3	3	4	4	5
79	8976	8982	8987	8993	8998	9004	9009	9015	9020	9025	1	1	2	2	3	3	4	4	5
80	9031	9036	9042	9047	9053	9058	9063	9069	9074	9079	1	1	2	2	3	3	4	4	5
81	9085	9090	9096	9101	9106	9112	9117	9122	9128	9133	1	1	2	2	3	3	4	4	5
82	9138	9143	9149	9154	9159	9165	9170	9175	9180	9186	1	1	2	2	3	3	4	4	5
83	9191	9196	9201	9206	9212	9217	9222	9227	9232	9238	1	1	2	2	3	3	4	4	5
84	9243	9248	9253	9258	9263	9269	9274	9279	9284	9289	1	1	2	2	3	3	4	4	5
85	9294	9299	9304	9309	9315	9320	9325	9330	9335	9340	1	1	2	2	3	3	4	4	5
86	9345	9350	9355	9360	9365	9370	9375	9380	9385	9390	1	1	2	2	3	3	4	4	5
87	9395	9400	9405	9410	9415	9420	9425	9430	9435	9440	1	1	2	2	3	3	4	4	5
88	9445	9450	9455	9460	9465	9469	9474	9479	9484	9489	0	1	1	2	2	3	3	4	4
89	9494	9499	9504	9509	9513	9518	9523	9528	9533	9538	0	1	1	2	2	3	3	4	4
90	9542	9547	9552	9557	9562	9566	9571	9576	9581	9586	0	1	1	2	2	3	3	4	4
91	9590	9595	9600	9605	9609	9614	9619	9624	9628	9633	0	1	1	2	2	3	3	4	4
92	9638	9643	9647	9652	9657	9661	9666	9671	9675	9680	0	1	1	2	2	3	3	4	4
93	9685	9689	9694	9699	9703	9708	9713	9717	9722	9727	0	1	1	2	2	3	3	4	4
94	9731	9736	9741	9745	9750	9754	9759	9763	9768	9773	0	1	1	2	2	3	3	4	4
95	9777	9782	9786	9791	9795	9800	9805	9809	9814	9818	0	1	1	2	2	3	3	4	4
96	9823	9827	9832	9836	9841	9845	9850	9854	9859	9863	0	1	1	2	2	3	3	4	4
97	9868	9872	9877	9881	9886	9890	9894	9899	9903	9908	0	1	1	2	2	3	3	4	4
98	9912	9917	9921	9926	9930	9934	9939	9943	9948	9952	0	1	1	2	2	3	3	3	4
99	9956	9961	9965	9969	9974	9978	9983	9987	9991	9996	0	1	1	2	2	3	3	3	4
N	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9

ing the proportional part corresponding to the fourth figure to the tabular number corresponding to the first three figures. There may be an error of 1 in the last place.

NOTE ON SIGNIFICANT FIGURES

Significant figures indicate the degree of accuracy in observed data and in the results computed therefrom. Thus, the statement that a certain measured length is 65.3 cm. indicates that it is nearer to 65.3 cm. than it is to either 65.2 cm. or 65.4 cm. In other words, the length has been measured to the nearest 0.1 cm., but it is not necessarily, and in general will not be, exactly 65.3 cm. Note that this length may be expressed in a number of different units, but the same figures (aside from zeros used to locate the decimal point) are always used. Thus, we may write 65.3 cm. = 653 mm. = 0.653 m. = 0.000653 km. Similarly, we may write 603 mm. = 60.3 cm. = 0.000603 km., or again 650 mm. = 65.0 cm. = 0.000650 km.

It is obvious that the 0 between the 6 and the 3 in the second example is of exactly the same character as the 5 which it replaced. Likewise, assuming that all these measurements are made to the nearest millimeter, the 0 to the right of the 5 in the last example has the same significance as the 3 which it replaced. Both of these zeros are entirely different from those used to locate the decimal point, which latter do not in any way indicate the accuracy of the measurement.

Definition. A significant figure is any one of the ten digits, exclusive of zeros used to locate a decimal point.

In order to secure all the accuracy possible yet avoid the appearance of unwarranted precision, and to save time, the data of observation, computation, and results, should contain only the proper number of significant figures. Usually it is not desirable to retain as significant figures more than one doubtful figure, e.g., the 3 in the first example given above.

Rule 1. In addition and subtraction no significant figures should be retained in any decimal place to the right of those in the number whose last significant figure is in the highest place.

Rule 2. In multiplication and division there should be the same number of significant figures in all the data, constants, products, quotients, and result as there are in the factor which has the fewest significant figures.

NOTE ON COMPUTATIONS

No physical observation can be made with perfect accuracy. Errors may arise from a number of causes, and among the most important of these are the errors of observation due to the limitations of the observer's powers. When only a single observation is made, the error arising from this cause may be estimated. When several observations of the same quantity are made, the possible error of the mean may be calculated, approximately, by taking the average of the differences between the mean and the separate readings. The possible error of a sum or difference is the sum of the separate possible errors. The possible error of a product or quotient expressed as a percentage is the sum of the possible errors of the factors also expressed as percentages.

Except for simple additions and subtractions, simple arithmetical processes are to be avoided. If the result should contain only three significant figures, the student is advised to use a slide rule. If four or more significant figures are to be retained in the result, use a table of logarithms.

The binomial theorem is frequently useful. For example $(1 + a)^2 = 1 + 2a +$ terms small in comparison with these two if a is small. Taking the square root of both sides, we have $\sqrt{1 + 2a} = 1 + a$. Hence, the square root of 1.004 = 1.002, and vice versa. Similarly, the cube root of 1.00400 = 1.00133, and vice versa. So for other powers.

NOTE ON GRAPHICAL REPRESENTATION OF RESULTS

In many physical experiments a series of observations is made in which all the quantities except two are kept constant. A series of corresponding values of these two variable factors is obtained experimentally. These results may be represented graphically on a sheet of coordinate or cross-section paper. Each pair of corresponding values is represented by a point on the cross-section paper. Locating a point on cross-section paper is like locating a city on a map when its latitude and longitude are known. The "latitude and longitude" of the point are called the coordinates of the point. That coordinate corresponding to latitude is called the "ordinate" of the point, and that coordinate corresponding to longitude is called the "abscissa" of the point.

Ordinary rectangular cross-section paper is usually laid off in squares by heavy lines either one-half inch or one centimeter apart each way. Each half inch, or centimeter, is again subdivided into either five or ten equal parts by lighter lines. Papers with ten subdivisions per inch, or per centimeter, are to be preferred to those with the coarser rulings. In logarithmic cross-section paper the subdivisions on the paper both horizontally (i.e., abscissæ) and vertically (i.e., ordinates) are not uniform, but are proportional to the logarithms of the numbers which are printed along the bottom and the left-hand margin of the paper. In "semi-logarithmic," or "arith-log," paper the vertical scale is logarithmic while the horizontal scale is uniform. In polar coordinate paper the ordinates are concentric circles and the abscissæ are radii of these circles. Usually the major divisions of the scale of angles are 10 degrees each, while the number of subdivisions depends upon the distance from the center of the circle. The radial divisions are uniform with each major division subdivided into either five or ten equal parts. Except in certain cases where one of the variable factors is an angle, the use of polar coordinate paper is undesirable.

In general, one begins by plotting observed experimental data upon ordinary rectangular cross-section paper, choosing suitable scales, and drawing smooth curves which best represent the series of plotted points. After a series of points has been plotted and the corresponding curve drawn, it may appear (1) that one of the variable factors may be represented more effectively in another way, or (2) that another type of cross-section paper may be used to advantage. As a rule it is best to choose the factors to be plotted and the type of paper in such a way that the "curve" is a straight line. For example, Boyle's law of gases is expressed by the equation $pv = c$, where p = pressure, v = volume, and c = a constant depending upon the mass of gas considered and its temperature. If the volume of a gas is altered in any way and its temperature is kept constant, the pressure exerted by the gas upon the walls of the containing vessel will be changed. If the observed values of the pressure and volume are plotted on ordinary rectangular cross-section paper as indicated above, the plotted points will lie (neglecting deviations due to experimental errors) upon a "rectangular hyperbola" that approaches zero values of p for large values of v, and vice versa. But if pressures are plotted as ordinates and *reciprocals of volume* as abscissæ, the plotted points will lie on a straight line passing through the point where $p = 0$, and $1/v = 0$. This

point is called the ***the origin.*** The straight line passing through this point in the direction in which abscissæ are measured is called ***the axis of abscissæ,*** and the one passing through it in the direction in which ordinates are measured is called ***the axis of ordinates.*** Thus, in the preceding example we would speak of the "axis of volume" and the "axis of pressure."

In the preceding example there is a degree of uncertainty about the relation between p and v when the hyperbola is obtained which is removed when the straight line is obtained, since any deviation from a straight line is at once apparent. If the relation is a linear one, the position and slope of the line at once give us the relation between the two coordinate factors. In ordinary rectangular coordinates the equation of a straight line is $y = mx + c$, where x is the abscissa of any point in the line and y is the corresponding ordinate, m is the "slope of the line," i.e., the tangent of the angle which the line makes with the x axis and c is the distance from the point where it intersects the y axis to the origin. This distance is called the "intercept on the y axis."

When one of the variables varies as some power of the other logarithmic paper may be used to advantage. Thus, the distance a body falls from rest in an interval of time t is given by the equation

$$d = \tfrac{1}{2}gt^2, \tag{1}$$

where g is a constant, the acceleration of gravity. If we take logarithms of both sides of this equation we obtain

$$\log d = 2 \log t + \log (\tfrac{1}{2}g). \tag{2}$$

Replacing $\log d$ by d', $\log t$ by t', and $\log (\frac{1}{2}g)$ by c, we finally arrive at the equation

$$d' = 2t' + c. \tag{3}$$

Hence, if we use logarithmic paper the plotted points lie on a straight line and the "slope" of this line is the power of t in equation (1), and the intercept of this line on the d axis is the coefficient of t in equation (1).

When we wish to find out how the value of one variable depends upon the value of the other, e.g., how far does a falling body fall in a given length of time, it is customary to plot the first variable as the ordinate and the second as the abscissa. Hence, in the foregoing example, experimental values of d are plotted as ordinates and those of t as abscissæ. To illustrate the manner of plotting and the use of different types of cross-section paper, the following data are shown in Fig. 25 plotted on both ordinary rectangular and on logarithmic cross-section paper.

t in sec.	0.0781	0.1563	0.2344	0.3125	0.3906
d in cm.	2.95	11.85	26.75	47.65	74.50

Because of experimental errors we should not expect either the parabola or the straight line to pass through all of the points, or through any of them, but it should pass close to all of them and the points should be distributed fairly uniformly on both sides of the curve. The drawing of straight lines or curves so as best to represent plotted points is largely a matter of experience. From the straight line in Fig. 25 we find that the relation between d and t is $d = 490t^{1.99}$. Compare this result with equation (1).

In choosing scales for ordinates and abscissæ, let 0.5 inch, or 1.0 cm., as the case may be, represent 1, 2, 5, or 10 units, and so on, but never 3, 6, 7, 9, 11, and so on. These units may be multiplied by powers of 10, i.e., $10^{\pm n}$ where

n is an integer. Four and multiples of four are permissible, but usually not desirable. In choosing the two scales their relative magnitudes should be considered. If the curve is a straight line, the scales should be chosen, if possible, in such a way that the line makes nearly equal angles with the two coordinate axes. In other cases, subject to the above recommendations, the scales should be chosen so as to extend the plotted points over about the same distance both horizontally and vertically. This does not apply to logarithmic paper, but does apply to both the rectangular and the semi-logarithmic.

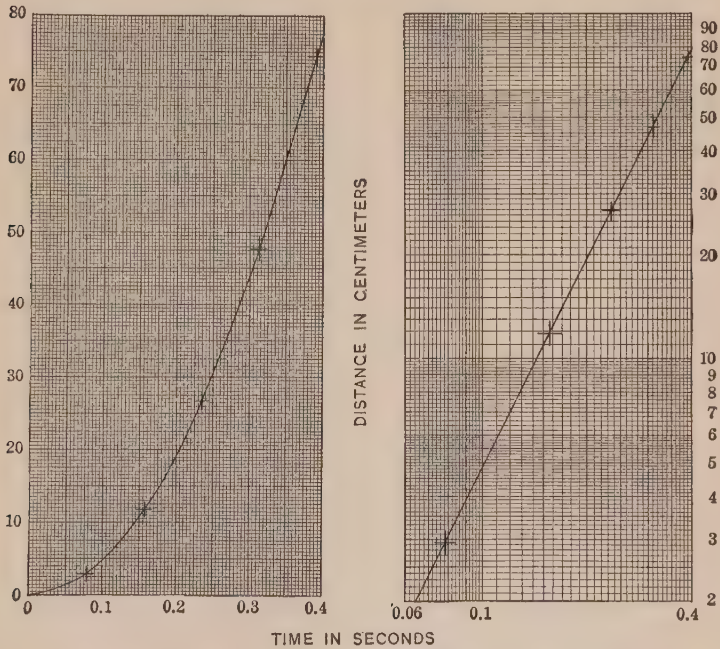


Fig. 25.—Showing Data for a Freely-Falling Body Plotted on Rectangular and Log-Log Cross-Section Paper.

Indicate the principal divisions of the scales along the lower and left margins of the paper, just as latitude and longitude are marked on ordinary maps. Do not mark individual observations on these scales nor at the points plotted on the paper. That is not done in most maps.

If possible, choose the scale large enough that all the significant figures can be readily distinguished on the plot. For example, let a difference of 1 in the last significant place at the right be represented by one of the minor subdivisions of the paper, or if the paper is not large enough to permit this, let a difference of 2, or 5, or even 10, be represented by one of these subdivisions. Avoid scales which are either too large or too small.

In plotting points a sharp pencil should be used. It is advisable to find the abscissa of the point to be plotted on the axis of abscissæ, then place a ruler or straight-edge at the latter point and parallel to the vertical rulings

of the paper. Draw a straight line about an eighth of an inch long at the approximate position of the plotted point. Repeat this operation for the ordinate and the point where the two short lines intersect is the position of the plotted point.

THE VERNIER

Ordinary metric scales are usually calibrated to millimeters, occasionally to half millimeters. If the subdivisions are smaller than this they are difficult to distinguish with the naked eye and lead to confusion. Similarly, inches are usually subdivided either into units of 1/16 inch or 1/32 inch. To measure lengths to fractions of millimeters or corresponding smaller fractions of an inch, we must estimate the decimal fraction of a division that the length exceeds the last whole division. In order to obtain greater precision in such measurements a vernier scale is often attached to the ordinary scale, hereafter referred to as the "principal scale."

The divisions on the vernier scale are usually slightly shorter than the subdivisions of the scale to which it is attached. If one subdivision of the latter is 1.0 mm. long, a subdivision of the vernier usually is 0.9 mm. long. The zero end of the vernier scale is set at the point where the length is to be read on the principal scale, and at some point the ath division of the vernier scale will coincide (or nearly coincide) with one of the divisions of the principal scale. (See Fig. 26.) Then the excess of the reading of the principal scale

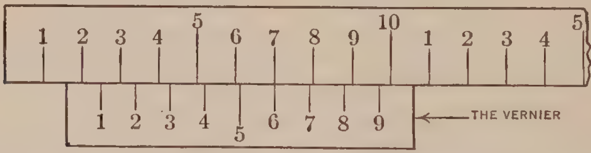


FIG. 26.—The Vernier. 6 on the Vernier Coincides with 7 on the Principal Scale, Indicating that the Reading at the Left End of the Vernier Is 1.6.

over the last whole division is $a/10$ mm. Sometimes the ath and the $(a + 1)$th division marks of the vernier will lie between two adjacent division marks of the principal scale. If they are symmetrically situated, the excess is $(a + 0.5)/10$ mm. If they are not symmetrically situated and if the accuracy of the measurement warrants it, one may estimate still more closely the value of the excess reading.

Before reading a vernier one must ascertain the relative sizes of the scale divisions on the principal and vernier scales.

THE MICROMETER

The micrometer is a piece of apparatus designed for even more accurate measurements of length than the vernier. In Experiment 6 on Thermal Expansion, a travelling microscope is used to measure the change in length of a rod. The microscope may be moved by a rack-and-pinion or it may be moved by a worm gear. For every complete turn of the worm the microscope moves, say, 0.5 cm. A circular scale divided into 50 or 100 equal parts is attached to the head of the worm. Assuming that one turn of the worm moves the microscope 0.5 cm and that there are 50 divisions on the head,

one division on the head corresponds to 0.01 cm. movement of the microscope. By estimating to tenths of a division on the head, measurements may be made to 0.001 cm. If a vernier is provided on the head, the uncertainty of an estimate is replaced by the certainty of the vernier. A microscope to which a micrometer is attached is often called a ***micrometer comparator.*** Micrometer calipers are used to determine the diameters of wires, etc. In making readings with micrometers they should always be set in just the same way. Thus, to avoid errors due to lost motion, the micrometer worm should always be turned in the same direction when making a final setting. In calipering wires it should always be set with the same light pressure, so as to avoid making indentations and yet have good contact. Some micrometer calipers are provided with friction devices to insure such adjustments.

LABORATORY REFERENCE LIBRARY

Every laboratory should have a library of reference books for the use of the students. The following books, among others, are especially valuable.

General

Edser, *General Physics for Students.*
—— *Heat for Advanced Students.*
—— *Light for Students.*
Goodwin, *Precision of Measurements and Graphical Methods.*
Neblette, *Photography Principles and Practice.*
Roebuck, *The Science and Practice of Photography.*
Tuttle, *The Theory of Measurements.*

Laboratory Manuals

Drew-Farwell, *Laboratory Experiments in Physics.*
Duff and Ewell, *Physical Measurements.*
Ferry and Jones, *Practical Physics.*
Ingersoll, *Laboratory Manual of Experiments in Physics.*
Miller, *Laboratory Physics.*
Millikan, *Mechanics, Molecular Physics and Heat.*
Millikan and Mills, *Electricity and Light.*
Reed-Guthe, *Manual of Physical Measurements.*
Taylor, *College Manual of Optics.*
Terry, *Advanced Laboratory Practice in Electricity and Magnetism.*
Watson, *Text-Book of Practical Physics.*

Tables

Chemical Rubber Publishing Company, *Handbook of Chemistry and Physics.*
Kaye and Laby, *Physical and Chemical Constants.*
Landolt-Börnstein-Roth-Scheel, *Physikalische-Chemische Tabellen.*
Smithsonian Physical Tables (Latest edition).

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